PhD-FSTM-2025-033
The Faculty of Science, Technology and Medicine

DISSERTATION

Defence held on 14/04/2025 in Luxembourg

to obtain the degree of

DOCTEUR DE L'UNIVERSITÉ DU LUXEMBOURG

EN *SCIENCES DE L'INGENIEUR*

by

Sinan KAASSAMANI
Born on 11 September 1989 in Baakline, (Lebanon)

THE CIRCULAR BUILT ENVIRONMENT IN LUXEMBOURG: INTERDISCIPLINARY STUDIES FROM SUPPLEMENTARY CEMENTITIOUS MATERIALS TO POLICY AND STAKEHOLDERS

Dissertation defence committee

Dr Felicia Norma Rebecca Teferle, dissertation supervisor
Professor, Université du Luxembourg

Dr Ariane König
Professor, Université du Luxembourg

Dr Joachim Hansen, Chairman
Professor, Université du Luxembourg

Dr Jean Frank Wagner, Vice-chairman
Professor Emeritus, Universität Trier Fachbereich 1

Dr Paul Schosseler
Director, Ministry of Economy of Luxembourg

This page intentionally left blank

THE CIRCULAR BUILT ENVIRONMENT IN LUXEMBOURG: INTERDISCIPLINARY STUDIES FROM SUPPLEMENTARY CEMENTITIOUS MATERIALS TO POLICY AND STAKEHOLDERS

Thesis supervision timeline

2020-2022 Prof. Dr.-Ing. Danièle WALDMANN-DIEDERICH, TU Darmstadt

2022-2024 Prof. Dr. Felicia Norma Rebecca TEFERLE, Université du Luxembourg

Prof. Dr. Ariane KÖNIG, Université du Luxembourg

Thesis defense jury members

Prof. Dr. Felicia Norma Rebecca TEFERLE

Université du Luxembourg

Thesis Supervisor

Prof. Dr. Ariane KÖNIG

Université du Luxembourg

Thesis Supervisor

Prof. Dr. Joachim HANSEN

Université du Luxembourg

Chair

Prof. Dr. Jean-Frank WAGNER

Universität Trier Fachbereich 1

Jury member

Dr. Paul Schosseler

Luxembourg Ministry of Economy

Jury member

Statement on the use of AI

I confirm that I have not employed any artificial intelligence tools to write any text. Their use was limited solely to improve the language in certain parts of the text. Moreover, I declare that the work submitted is entirely my own, completed during my enrollment as a candidate for the degree listed on the Title Page. I confirm that I have not received any degree from another institution based on the research contained in this work. Additionally, this submission incorporates original work that enhances the foundational research.

Abstract

The transition to a regenerative sustainable model in the construction sector is one of the pathways to reducing negative impact and aligning with the United Nations Sustainable Development Goals. Cement production is a major environmental burden, contributing nearly 8% of global CO_2 emissions. This research explores circularity in the built environment through an interdisciplinary approach starting with material technology and specifically the potential of using secondary waste materials, particularly Gravel Wash Mud (GWM), as Supplementary Cementitious Materials (SCMs) to reduce reliance on ordinary Portland cement (OPC) and promote more sustainable construction practices.

By repurposing industrial byproducts from gravel mining in the Greater Region (Luxembourg, France, Belgium, and Germany), this study aligns with circular economy principles that prioritize waste valorization and resource efficiency. The findings confirm that such materials, when thermally activated and incorporated as a partial cement substitute, enhance concrete performance while reducing its carbon footprint. However, despite the technical feasibility of such materials, their widespread adoption remains limited due to some challenges.

Beyond material innovation, following into the interdisciplinary approach to assess the broader systemic factors influencing circularity in construction, it examines the role of policy frameworks, stakeholder networks, and industry dynamics in shaping the circularity landscape and sustainable material adoption. By mapping these interactions, the study identifies key barriers to change and proposes actionable strategies for fostering a regenerative circular economy—one that not only minimizes waste but also restores and revitalizes resources within the built environment.

This research underscores the need for systemic transformation in construction practices, advocating for an integrated approach that combines material science, policy adaptation, and industry collaboration to drive meaningful progress toward a more resilient and regenerative future.

Keywords: regenerative circular economy, sustainability, cement, concrete, secondary materials, GWM, waste valorization, policy, stakeholders.

This page intentionally left blank

Acknowledgements

I would like to thank all the people who made this journey worthwhile and possible, and from whom I learned immensely during this four-year journey including my supervisors, colleagues, friends, and family, and everyone who contributed to this research with their time, resources, knowledge, and interest. None of it would have been possible without every single one of you.

Thank you very much from the bottom of my heart to all of you.

A very special thanks to my supervisor Prof. Dr. Félicia Norma Rebecca Teferle for being a role model and for her support in this journey on so many levels, but above all in valuing interdisciplinary research and giving me the opportunity to develop my work into this direction.

Immense gratitude to my mentor Prof. Dr. Ariane König for introducing me to the world of sustainability science and social ecological systems, for the amazing and inspiring discussions, for all the wonderful books, for trusting my learning process, for the rich input into my thesis work and for welcoming me into her group for a truly immersive experience. I am very grateful for your support and guidance.

Thank you to Prof. Dr. Joachim Hansen for kindly allowing me to use the department laboratories for my research and for being a valued CET and jury member.

Thank you to Prof. Dr. Jean-Frank Wagner for his support, expert input, and presence in my CET and jury.

Thank you to Dr. Paul Schosseler for his time, availability, and productive discussions, and for being a jury member.

Thank you to Prof. Dr. Danièle Waldmann with whom I started this research journey, for working together, and for her supervision and support during project CO2REDRES. I am extremely grateful.

Thank you to Interreg Greater Region and Feder for funding the research for project CO2REDRES. And thank you to the project team from the Universities of Trier, Lorraine, and Liège. Thank you to the talented Prof. André Lecomte it was a pleasure to know you, Dr. Romain Trauchessec, Dr. Baptiste Luzu, Dr. Karlis Kukemilks, Dr. Oscar Baeza Urrea, Prof. Luc Courard, Dr. Moussa Ka and Mr. Gaspard Chantrain. Thank you to the CO2REDRES project partners, and in special Cimalux and Dr. Claude Simon and Mr. Mirko Cecchetto for allowing the use of their labs and providing technical support and materials for this research. Thank you also to Mr. Paul Wertz of Carrières Feidt, Dr. Frank Hesselbarth of Saint-Gobain Weber, and Dr. Olivier Martinage for their interest in this research. Thank you to the Administration des Ponts et Chaussées laboratory in special Mr. Georges Blasen, Mrs. Karin Maas, and Mr. Marco. Thank you too to Dr. Zornitza Tosheva of the University of

Luxembourg Physics department. Thank you also to all the industrial partners of project CO2REDRES who provided support and materials for testing.

Thank you to all the research participants who gave me their precious time and opened their doors to contribute to research in circular economy. Your passion and future visions made me go beyond my initial plans, and showed me how powerful a conversation can be.

Thanks to the admin team at the University of Luxembourg for making the PhD life easier, in special Heidi Backstroem, Rita Giannini and Odile Marois. Thank you for the concrete lab research support team at the halles d'essais: a huge thank you to Marc Seil, Ed Weyer and Gilbert Klein for providing technical support. Thank you to the urban water management lab for allowing me to run my experiments, especially thankful for the memory of the remarkable Mr. Markus Schlienz, and the company of Dr. Paula Tafalla and Dr. Irene Salmeron during my time there.

Thank you to the social ecological systems team, in special Sophie Zuang for the inspiring conversations. Thank you to Maximillian Klein for the office company, Stefan Weiss, Jacek Stankiewicz, Ana Panzani Alves, Leoni Vandrey, Hamid Asadi and Nima Rezaei for being valued colleagues and sharing the journey.

I am also truly grateful for the DoE friends with whom I share countless memories, Dr. Lorenc Bogoviku, Dr. Hooman Eslami, Dr. Tarik Camo, and Anna Tokareva, for their support over these 4 years of hard work and their true friendship. A special thank you to my master thesis mentor Dr. Vishojit B. Thapa whose research and guidance were essential for the success of my work in this PhD. A great thanks to my MSc. friends Katia Santos, Lorenc Bogoviku, Nabina Shrestha, Tatiana Stoia, and Petros Lazaridis for their support and making it feel easier than it is to go through a PhD.

Thank you to my friends Dr. Rana Comertpay and Mario Riga for being part of this journey since day 1 of my academic journey in Luxembourg from close by or through a distance.

Special thanks to Dr. Silvia Venditti and Suzanne Biwer for their help and friendship during this time.

To the uni lu friends, you are numerous, and I appreciate the time I spent with every one of you during the last years.

I am also very grateful to the students who trusted in my support and guidance for their thesis projects, or who shared an idea, a conversation, or an article, you all made me a better researcher.

A special thank you to my family, my parents Salwa and Ghassan for their unconditional love and unwavering support and always cheering me on with the greatest energy, to my siblings Thuraya, Soha, and Hadi whose care and support always keeps me going. To my beloved Brazilian family os Saabs in special Linda, obrigado pelo amor e pelo enorme suporte e por apoiar minhas escolhas de vida e vibrar pelas minhas conquistas.

Thank you to my friends who made Luxembourg home. Thank you, Luana, Leticia, Anna, Nils and Tatiana for the warmth of home. Thank you Davor for your true friendship. Thank you, Masha, for encouraging me to pursue my dreams. Obrigado também para Maria e Cica pela amizade de milhares de kilometros durante esses anos.

Finally, I cannot forget to mention the inspiring professors of my alma mater, the late prof. Jose Oswaldo Ribeiro Moreira for introducing me to the academic world very early on, and the talented professors prof. Malu Viana, prof. Dr. Edna Alves Oliveira, and prof. Dr. Mario Lucio Pereira Junior for encouraging me and believing in my potential in research.

A heartful thank you to Tootsie whose presence makes life a lot more fun and worthwhile.

This page intentionally left blank

SCM	Supplementary Cementitious Material(s)
CE	Circular Economy
SDG	Sustainable Development Goals
PC	Portland Cement
OPC	Ordinary Portland Cement
GHG	Greenhouse Gases
GWM	Gravel Wash Mud
TGA	Thermogravimetric analysis
SAI	Strength Activity Index
CH	Calcium Hydroxide (Portlandite)
CSH	Calcium silicate hydrate
ITZ	interfacial transition zone
GGBS	Ground granulated blast furnace slag
ASR	Alkali Silica Reaction
MK	Metakaolin
PSD	Particle Size Distribution
AAB	Alkali Activated Binder
LC3	Lime Calcined Clay Cement
LCA	Life Cycle Assessment
EC	European Commission
ISO	International Standardization Organization
PCDS	Product Circularity Data Sheet
LEED	Leadership in Energy and Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
LENOZ	Lëtzebuerger Nohaltegkeets-Zertifizéierung
EDTA	Ethylenediaminetetraacetic acid
LBC	Living Building Challenge
EU	European Union
DPP	Digital Product Passport
XRD	Xray Diffraction
XRF	Xray Fluoresecence
PNGDR	National Plan on Waste and Resource Management
PNEC	Integrated National Energy and Climate Plan

Table of contents

List of figures

List of Tables

This page intentionally left blank

Part I | Setting the research scene

This page intentionally left blank

1 Introduction

The built environment plays a crucial role in global sustainability challenges and has been the object of numerous studies, with material consumption, waste generation, and carbon emissions significantly impacting ecological and economic systems. As the transition toward a circular economy gains momentum, this thesis follows an interdisciplinary approach to address sustainability, one that integrates material innovations, stakeholder engagement, and policy frameworks. This research explores the role of supplementary cementitious materials (SCMs) in reducing environmental impact of conventional Portland cement, the influence of key stakeholders in driving sustainable practices in Luxembourg, and the effectiveness of national policies that support circularity in construction. By bridging material science, policy analysis, and stakeholder dynamics, this study aims to contribute to a more holistic understanding of sustainable development in the built environment.

1.1 Background and context of the research

At the intersection of the circular economy and greener futures, with a shared objective of creating better living spaces across all phases of the construction lifecycle, lies a dynamic realm of sustainability concepts. These concepts continue to be explored through a multitude of individual and collective actions, conceived, planned, and implemented in ways that surpass our vision of a sustainable built environment. From long standing ancestral building techniques to cutting-edge technological advancements, a convergence of diverse approaches shapes the present reality. Within this context, there is an undeniable sense of urgency, recognizing the high stakes involved, but also an abundance of opportunities for positive change in such complex systems. This urgency for transition is furthermore supported by the numbers. According to the United Nations Environment Programme (UNEP) the building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy produced [1]. Moreover, since 1970, the global population had doubled, but the global resource extraction has tripled as shown in Figure 1. Non-metallic mineral extraction, including materials such as sand, gravel, clay, and other materials used in concrete production (in blue in the graph), has seen the highest growth among all four material categories over the past five decades. The extraction of these resources increased fivefold from 9.6 billion tons in 1970 to 45.3 billion tons in 2020, growing at an average annual rate of 3.2% [2]. This surge is largely driven by infrastructure expansion and urbanization, and those materials now account for nearly half of global material extraction, reflecting a shift from biomass-based economies to mineral-intensive industrialization.

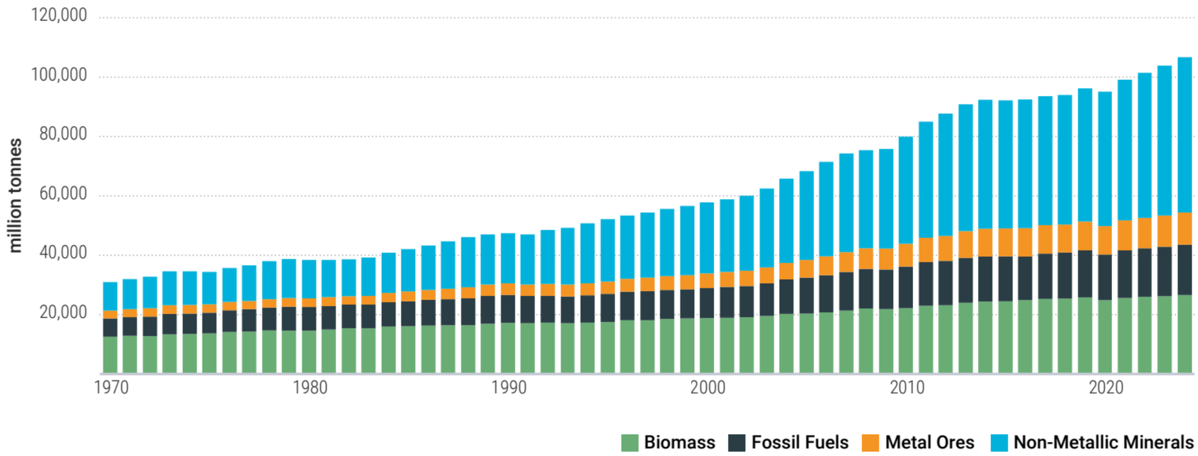


Figure 1: Global material extraction from 1970 to 2024 in mt [2].

With a diversity of approaches and strategies to create a sustainable building landscape across scales ranging from building materials to built cities, the solutions tend to frequently revolve around energy and resource efficiency. However, if we start regarding this undertaking through an interdisciplinary lens, it becomes clear that there is much more to a symbiotic harmonious existence of the built environment in its context than just carbon emissions. While the focus in this thesis is on the circularity landscape in Luxembourg and the use of SCM in the Greater Region, it is important to highlight that this is not the only solution neither it is claimed to be the best option, but just one of the many answers to the evolving problem of sustainable built environments.

Whether it is green buildings, passive houses, circular design, or nature-based solutions, the methods might differ, but one important goal is at the center: ultimately achieving a long-lasting regenerative sustainability culture in buildings and infrastructure as cities move forward into more resilient modes of living and doing, in partnership with the natural system life belongs to, beyond the techno-centric climate change mitigation agenda in the short term run.

In short, the motivation behind this research lies in three key factors at three scales:

(1) *The global scale* – with climate change mitigation being at the forefront of international agendas, research in sustainability science is needed to advance on that front and work towards challenging the status quo and not only reducing emissions but also aspiring towards sturdy solutions that make life better for all living creatures.

(2) *The holistic approach scale* – In order to create enabling conditions to a transition process that decouples resource use from human wellbeing and negative environmental and social impacts, single isolated solutions are not going to deliver results when what is needed is a systemic transformation that reconfigures unsustainable patterns of resource use into a model that fits within planetary boundaries.

(3) *The construction industry scale* – locally and internationally, as traditional cementitious materials are depleting due to limited supply and over-extraction added to environmental restrictions, research into alternative solutions at material level becomes ever more important. And as an addition, restrictions on landfill use for industrial waste and quarrying and mining byproducts make it ever more essential to perceive the value of materials differently and take tangible action at scale.

1.2 Research problem and objectives

The built environment is one of the largest contributors to global resource consumption [3] and waste generation as well as carbon emissions, posing significant challenges for sustainability in both short and long term. Traditional practices that are focused on extraction, production, and disposal, exacerbate resource depletion and environmental degradation. The transition to a circular economy (CE) presents an opportunity to rethink and redesign these systems to reduce waste, improve resource efficiency, and promote sustainability. However, this shift requires more than just technical innovations; it demands systemic changes in the industry and the adoption of practices that consider the interests and contributions of diverse stakeholders. The lack of a coherent vision [4], cohesive policies [5], and the misalignment of stakeholder priorities and engagement [6] can constitute barriers that hinder progress toward circularity in the built environment.

This research aims to explore and analyze different types of quarry industrial waste or by products that have cementitious properties i.e. can be used as substitutes and/or additions to cement in concrete, called supplementary cementitious materials (SCM). SCM inherently have an element of circularity — in closing the loop of quarry production models by valorizing waste — and an element of sustainability — in reducing carbon emissions and landfilling in cement production and gravel quarries respectively. Beyond the experimental part, the research also delves into a qualitative aspect that aims to identify the challenges that exist and prevent the implementation of effective circular practices. One of the key objectives in this part is to understand how stakeholders—including policymakers, businesses, designers, contractors, and end-users—interact and influence the implementation of CE principles. By mapping these interactions and identifying symbiotic or conflicting relationships, the research aims to unveil stakeholder priorities and how they align with circularity objectives, so that as a next step in the future these outcomes can be used to propose strategies of integration and collaboration between the involved stakeholders since the success of circular economy initiatives in the built environment depends on the engagement and collaboration of those players. Another key objective is to understand the impact of policy on circularity through an ontological lens since policymakers play a role in setting regulations and incentives that can affect circular practices. This study emphasizes the need for inclusive policymaking and stakeholder collaboration to create an enabling environment for circular economy practices. Ultimately, the research aims to provide a sound scientific basis on the potential of SCM use in the Greater Region and moreover, actionable insights that could guide policy and stakeholder alignment for a more sustainable and circular built environment.

The objectives can be summarized as follows:

- To explore and analyze quarry industrial waste and by-products with cementitious properties (SCMs) that can substitute or complement cement in concrete.
- To investigate the circularity potential of SCMs by assessing their role in reducing carbon emissions and landfill use, and in valorizing quarry waste.
- To provide a scientific basis for the use of SCMs in the Greater Region, supporting both environmental sustainability and circularity.
- To examine barriers to implementing circular practices including the use of SCMs in the built environment beyond technical factors.
- To better understand stakeholder dynamics and how it influences CE implementation by identifying stakeholder priorities and alignment/conflicts with circular economy goals to inform future strategies for integration and collaboration.

- To analyze the role of policy through an ontological lens to assess how regulations and incentives influence circular practices.
- To deliver actionable insights to guide stakeholder alignment and policy development toward a more sustainable built environment.

1.3 Significance of this research

Sustainable development is at the core of global efforts to ensure a prosperous and equitable future for our planet and its inhabitants, human and non-human. As the planetary boundaries that constitute a safe operating space for humanity have since their definition in 2009 by *Rockström et al*. [7], been exceeded according to a recent study published in 2023 with only two boundaries within the established safe limits [8], all efforts for reversal of such trends are welcome.

Connecting to this scenario, the research conducted for this thesis visits multiple facets of the sustainability conundrum in the construction industry starting with material technology and ending in a snapshot of the construction ecosystem in Luxembourg. As a result of this spectrum, the research covers 4 of the 17 Sustainable Development Goals (SDGs) developed by the United Nations (UN). By integrating these interconnected goals into research, we address and contribute to the development of said goals through SDG9, SDG11, SDG12, and SDG13. All the actions that were developed in this thesis relate in one way to one or more of the SDGs and are detailed in Table 1.

In addition to the SDG view presented in Table 1, the significance of a holistic approach to the subject of research lies in its ability to produce a comprehensive and integrated understanding of complex issues, in specific sustainability in the built environment, through different lenses: material technology, stakeholders, and policy.

When the question of sustainability is raised, often CO_2 emissions are the sole focus, and it is already known that this is just one element of the problem-solution system. Carbon-monomania is defined by the obsessive preoccupation with one single environmental impact, the carbon emission.

Table 1. SDG vs. research actions significance.

SDG	Research action or question related
	- The research of ways to use new and not previously tested SCMs to reduce carbon emissions in the industry. - The enhancement of research and innovation in the industry through project CO2REDRES collaboration with industrial partners.
	- The preservation of nature through reducing land-use intensity by employing secondary raw materials and industrial waste in novel concepts. - The contribution to understanding the local construction industry ecosystem through the lenses of policy and stakeholder interactions to build more sustainable cities.
	- Contributing to circular business models: curbing resource depletion and waste generation by valorizing secondary raw materials. - Reducing waste generation through studying and applying circular measures.
	- The reduction of emissions compared to conventional clinker Portland cement use, one step further in helping the industry reach its net-zero / net-positive goals. - Promoting positive and regenerative action through ideas, knowledge creation and scientific research to meet the climate targets.

According to *T. Parrique* author of *Ralentir ou Périr*, solving the Carbon issue is like solving one face of the Rubik cube - necessary but not enough, there is more to a social-ecological transition than carbon [9]. Therefore, the interconnectedness of issues requires a systemic understanding of the challenges that the research studies and integrated solutions that address multiple sides of the sustainability problem rather than just a specific isolated part as an outcome. Holistic approaches to research often involve integrating knowledge from various disciplines that are contextually relevant to the problem, which leads into the interdisciplinary aspect of this research that will be detailed further in section 1.6.1.

1.4 Research questions

The research questions that create the base of this thesis work can be discovered in two parts, the relation between each of those parts is defined and discussed in the next sections of this chapter. However, the broader connection is given through a common field: the study of circularity, which represents the link that connects the micro-level (i.e. the material innovation part) to the macro-level (i.e. the systemic part).

1.4.1 The use of SCM as an alternative to Portland cement-based concrete.

a. What are the key chemical and physical properties that influence the selection of potential cement substitutes in the Greater Region?
b. How do these properties affect pozzolanicity or pozzolanic activity?
c. Is the valorization of clay based secondary waste materials from the Greater Region to be used as supplementary cementitious materials (SCM) possible?
d. Is there a correlation between pozzolanic properties measured experimentally and the strength activity index with the mechanical performance of paste and mortar specimens containing those SCM?
e. What can a framework for decision making on the potential of such materials in the industry be like?
f. What are the implications of the findings for scaling up the use of these materials in circular solutions in the industrial cement production?

To address these questions, a comprehensive experimental methodology was employed through detailed laboratory work as described in chapter 3, and as informed from the literature review. The research involved the collection and characterization of various quarry industrial wastes and by-products with potential cementitious properties (see part 3.2). These materials were subjected to a series of tests to evaluate their chemical composition, mineralogical structure, and physical properties to determine their suitability as supplementary cementitious materials (SCMs). Standardized tests, such as described in section 3.3 of the methodology chapter, were used to analyze the materials' properties and pozzolanic activity. Additionally, selected SCMs were incorporated into concrete mixes in varying proportions to assess their performance in terms of mechanical strength as shown in the results section in chapter 4. The results provided empirical data on how these materials can partially replace cement while maintaining or improving concrete performance (see 4.4 and 4.5). This experimental approach not only validated the technical feasibility of using quarry waste and industrial by-products as SCMs but also laid the foundation for exploring their contribution to circularity and sustainability in the built environment and carrying the research further in the context of project CO2REDRES by partner universities. Furthermore, questions e and f were addressed in the same chapter through the results of the data analysis obtained from answering the previous questions.

1.4.2 The ecosystem of the circular economy in the built environment in Luxembourg through the lenses of stakeholders and policy.

g. How do experts from different backgrounds in the field perceive circularity?
h. Who are the stakeholders and how are they connected?
i. What are the challenges that circularity faces in the built environment?
j. What are the policies that affect circular practices and how are they related ontologically to the transition towards a holistic circular economy model?
k. How does the interaction between stakeholders and the public policy content shape the uptake of new material technologies developed in projects like CO2REDRES?
l. What constitutes systemic solutions that can overcome the mapped challenges?

For the qualitative research, a complementary methodology was developed using interviews with local and national experts as described in Chapter5 as means of data collection, where the research design and approach are discussed in section 5.1 and the data collection method and interview design is described posteriorly in section 5.2. The answers to the research questions g to l are then discussed in Chapter 6, where the research findings are presented under the title of data analysis. In the subsections of 6.1.1 the views of different experts are explained with a further dive into divergences and similarities as well as a discussion on circularity as opposed to sustainability to show the depth of how the understanding of different concepts can influence outcomes and practice. The analysis then goes further in the other sections to describe the challenges and barriers to circular strategy and practice implementation to answer the related research questions. Further into the chapter the stakeholder interactions mapped form the interview data are presented, and finally the part on policies, starting with a map of the existent policies and continuing with an analysis of their context in Luxembourg.

The different parts of this chapter then culminate in a summarized outcome which is a system of integrated solutions (Figure 79) to overcome the mapped challenges in this context.

1.5 Projects CO2REDRES and CO2REDSAP

This section describes the two projects that are part of this thesis to prepare the reader for the upcoming parts that are complementary yet distinctly presented in the methodological and data analysis parts since they pertain to two projects.

1.5.1 Project CO2REDRES

Along the pathway to net zero emissions, the construction industry has an immense road to pursue mainly by reducing its carbon footprint, and one of the solutions resides in changing the way materials have been used for long. Ordinary Portland Cement (OPC) based concrete has been known to be a major contributor to carbon emissions with the sector responsible for 6 to 7% [10] of the global anthropogenic emissions due to (i) the decarbonation of limestone to form lime in the clinker production process (ii) as well as the high energy intensity of the cement production process overall [11]. It is estimated that the amount of clinker used in cement is roughly proportional to the carbon dioxide emissions released in cement manufacturing [12]. Therefore, the necessity of finding alternatives to the status quo in the industry has become a pressing matter to meet the objectives of carbon neutrality and sustainability goals.

Since a material's environmental impact is frequently associated with its effect on climate change and greenhouse gas emissions (GHG) [13], green concrete concepts involve partially replacing the highest CO2 footprint component, which is cement, by other materials. SCM are one of these promising concepts that allow this reduction to happen [14], [15], [16], [17].

SCM often have benefits associated with their use and their cementitious properties. They are often employed to improve workability, increase strength and enhance durability of concrete mixes through hydraulic or pozzolanic activity, besides reducing the OPC content [18], [19]. Examples of SCM include ground granulated blast furnace slag, coal fly ash, rice husk ash, silica fume and calcined clays such as metakaolin among others [14], [18], [20]. The pozzolanic action of SCMs is the product of the presence of amorphous phases of silica and alumina that can react with calcium hydroxide present in cement to produce stable compounds with cementitious properties just as is the case for the normal OPC hydration reaction which takes place between cement and water to also produce C-S-H compounds [21]. The pozzolanic reaction however is slower than the hydration reaction, but by consuming the excess calcium hydroxide (CH) present in the system and producing additional C-S-H family compounds it helps in reducing the pores in the matrix and improving its strength and reducing permeability as well as allowing grain size refinement which improves the transition zone densification due to smaller CH crystals [22]. It is also dependent on other properties such as particle size distribution and specific surface area of the pozzolan material [23]. The degree of pozzolanic action often referred to as the pozzolanic activity is measured by the amount of CH fixed by the pozzolanic material in the binder matrix [21].The amount of pozzolans used varies from 5 to 40 wt.% of OPC depending on the physical properties and reactivity of the SCM [23].

Natural pozzolans and in particular clays and calcined clays as well as clay rich waste materials have been at the center of research efforts for constituting feasible and suitable partial substitutions to OPC [15], [22], [24], [25], [26]. Gravel wash muds (GWM) and similar quarry wastes rich in clay content also constitute an important source for SCM use and examination [24], [25], [27]. Many authors use a range of tests to detect pozzolanicity through direct and indirect methods. The direct methods as the name suggests are related to chemical, thermogravimetric and mineralogical measurements that evaluate the amount of portlandite in a compound over time, thus giving an indication on the pozzolanic reaction. The indirect methods are related to the measurement of physical properties of test samples such as compressive strength, calorimetry, and conductivity tests [28], [29]. In short, this is the scientific technical background that project CO2REDRES is based on and which is further detailed in the literature presented in chapter 2 part 2.1.

This research is part of an Interreg[1] Greater Region project entitled CO2REDRES (Figure 2) which is a partnership between the Universities of Luxembourg, Trier, Lorraine and Liege together with industrial partners of the cement and construction materials industry in the region. As each partner university had a role, the one taken by the University of Luxembourg is detailed in this doctoral thesis. Considering the optimization processes that happen through thermo-mechanical treatment of clays [30] and consequently clay rich GWMs, 7 novel sample materials were investigated through a large series of mortar and binder mixtures with a predefined OPC substitution rate at 20 wt% and three different calcination temperatures to be able to draw out conclusions on the best treatment options in line with the data obtained on chemical and mineralogical composition, physical characterization, and direct and indirect pozzolanicity potential assessment.

Figure 2. Infographic of project CO2REDRES. (developed by the author)

[1] Interreg Greater Region is a cross-border cooperation program covering Luxembourg and certain parts of Germany, Belgium and France and is funded by the European Union.

1.5.2 Project CO2REDSAP

As project CO2REDRES came to an end, the choice of research continuity took a turn to new interests which lay beyond the experimental nature of a chemistry and concrete lab setting, as questions arose as to why such studied solutions are not applied in the industry at a large scale, or sometimes even at all. As a result, the research on circularity in the built environment with a specific interest in stakeholders and policy came to light. Project CO2REDSAP is quite restricted in the scope sense because it studies a very specific aspect of circularity, that of materials, and in the realm of materials more specifically clay-based SCM. Therefore, the decision was made to amplify the scope towards circularity in the built environment as a whole in Luxembourg while keeping a link to material technology. The nature of the research in this part required the need of other methodologies that can answer the research questions, which led to the development of tools and methods adequate to a qualitative research approach that is detailed in chapter 5, giving an interdisciplinary aspect to this thesis.

1.6 Integration of quantitative and qualitative approaches

Since the two projects explained in the previous section are distinct, an integration for the completeness of this thesis work is an important step in transforming the two ideas into a connected whole that represents more than the sum of its parts and that ultimately brings more strength to this interdisciplinary approach. In this section the explanation of this interdisciplinary approach as well as the connection between the material and the stakeholder and policy part are presented.

1.6.1 Explanation of the interdisciplinary approach

In a world grappling with wicked problems like climate change and sustainable transitions, *Ravetz and Funtowicz's* [31] concept of post-normal science becomes one that is worth discovering as the questions that scientists study, start to surpass the boundaries of applied science. The approach transcends traditional disciplinary boundaries, embracing a holistic perspective that accounts for complexity, uncertainty, urgency, societal impacts, and other critical system aspects. Although it is present as a problem-solving concept in social science, certain principles are highly relatable to engineering, especially when we look at the context that research is embedded in. The challenge of achieving more sustainable built environments passes through targets of zero carbon emissions and using suitable construction materials but that cannot possibly be the end and only answer.

Solutions ultimately extend to other areas of knowledge and research embodying the complexity of the problem at hand. The built environment might well be made of bricks, beams, and columns, but it is highly influenced as research shows, by multiple stakeholders, regulatory and policy drivers, technology and resource availability, organizations, awareness levels, financial and economic factors, among others [32], [33], [34], [35], [36]. This research acknowledges the importance of post-normal science in addressing complexity but does not claim to entirely fit in this category as it traverses applied science and does not include representatives from all relevant stakeholders in the different processes of research, especially in the quantitative parts related to project CO2REDRES.

The construction engineering industry exemplifies the need of holistic approaches, with its intricate processes and diverse inputs required for massive, sophisticated outputs like buildings and infrastructure projects that are essential for life. These complexities highlight the indispensable role of science, particularly its interdisciplinary components, in addressing such multifaceted challenges.

Along the way, many questions were raised, such as which sort of science provides answers to the research problems at hand? Which methods of problem solving should be used? How to approach complex topics in research? Is it enough to stick to a positivist laboratory view of science isolated from the ecosystem in which it happens? All those questions and many others led to the choice of the mixed methods research to get answers that are not embedded in one unique discipline, neither discoverable through one methodology only.

The rationale for combining quantitative and qualitative methods was exactly to capture the picture through a different lens, beyond the scope of a single way of doing and knowing. This allowed to dive beyond the material technology part of the thesis and venture into circularity in the built environment as a larger topic to understand factors other than chemical and physical suitability of materials, that impact the adoption of circular solutions and the overall sustainability of the sector and its connection to circular practices, thus putting further into evidence the interconnectedness of the modern problems that science faces nowadays. By combining methods, research tools, concepts, perspectives, and theories interdisciplinarity as a concept materializes and stands out in the research becoming a force that creates a comprehensive understanding of a system much bigger than each discipline isolated. Further into the interdisciplinarity aspect [37], [38], and on top of spanning more than one academic discipline, CO2REDSAP incorporates the inputs of non-academic stakeholder groups to create a comprehensive understanding of the problem at hand based on real-world perspectives and research results that can possibly have application in both scientific and societal practices. Although the qualitative part of this thesis would still benefit from a wider exposure of its outcomes to interested society groups who are non-experts on the built environment topic, it was based from the initial conception on the idea of getting expert info input from contributors beyond academia, which in a way represent various societal circles in their views and this got consequently reflected in the research results discussed in this thesis.

Figure 3 illustrates the interdisciplinary approach in this research project where the study system boundaries are enclosed within the field of the built environment and more specifically sustainability and circularity. In a disciplined methodology the three aspects would be researched separately in closed systems that consider each a subject by itself. An interdisciplinary approach would still use experimental laboratory-based research methodologies to solve most of the material technology research questions, and a qualitative approach to answer the policy and stakeholder questions, however the three research subjects are viewed as intertwined and the answers that are sought lay precisely at the intersection of those fields of research and methods of inquiry.

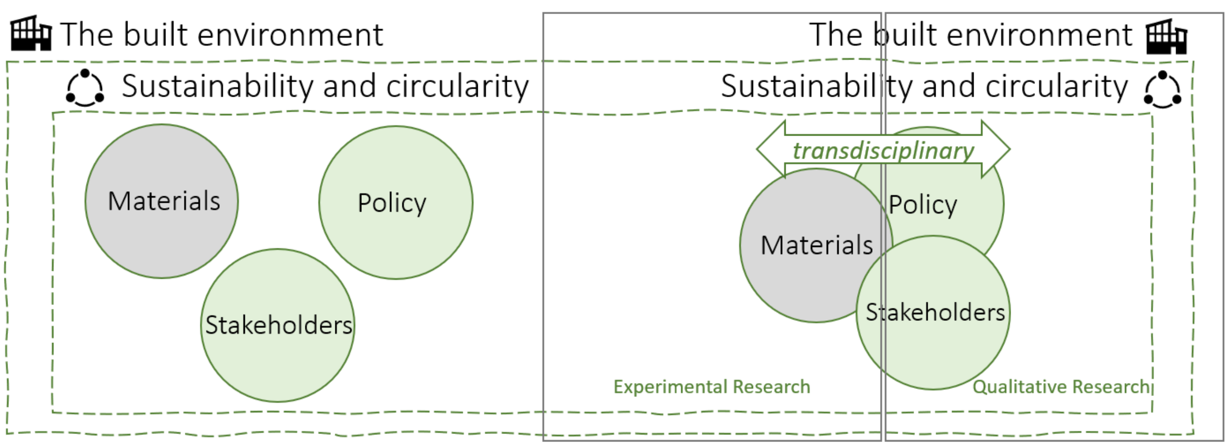


Figure 3. The research outline from disciplinary (left) to interdisciplinary (right).

The construction materials industry exists in a social-political scenario that makes the technical results of a materials-based research very relevant to and influenced by current policies and stakeholder group interactions. Transcending the chemistry and concrete laboratories of the university and its partners to the meeting rooms of industry, academic, and public administration representatives presents the possibility of connecting the technicalities of innovation in material science to the wider setup that includes a portion of society that influences practices and takes decisions that affect the uptake of such innovations. This gives the research an edge to innovate and look at questions that are often disregarded by disciplinary methods.

1.6.2 The connection between the qualitative and quantitative approach

The connection between the qualitative and quantitative parts of this monograph is framed around the integration of SCMs in circular construction by linking material-level feasibility (quantitative) with policy and stakeholder dynamics (qualitative). Although the interrelation is not obvious at a first glance due to the field of SCM being restricted to one material and the qualitative part referring to circularity in general and not only of SCMs, this is partially due to the fact that the research would have been too narrow and with not enough input as there is no specific policy in place that treats just the question of SCM, neither is there a diverse stakeholder body that is working with these materials. Therefore, the decision was taken to widen the scope of project CO2REDSAP and then draw parallels throughout the analysis of the qualitative part as to which pieces fit in and relate to project CO2REDRES directly.

1.6.2.1 Material feasibility and valorization (quantitative Part → SCMs in concrete)

This part provides the technical foundation by examining how waste from quarry gravel production in the Greater region can be used as SCMs. It involves laboratory tests, performance evaluations, and comparisons to existing SCMs or standards. The circularity aspect here is focused on material-level reuse and reduction/elimination of waste.

1.6.2.2 Circularity in the built environment (qualitative Part → policy & stakeholders)

Since specific policies for SCMs are lacking, broadening the scope to circularity in general helps contextualize why SCM valorization is challenging and how systemic circularity approaches could facilitate it. This section investigates regulatory gaps and stakeholder roles in adopting circular solutions in the built environment in a broader way but can always relate back to SCMs or any other circular practice. It aims to bridge the gap between technical potential and real-world implementation.

1.6.2.3 *The connection: A systemic approach to SCM adoption in circular construction*

The quantitative findings on SCM feasibility in CO2REDRES feed into the qualitative discussion by demonstrating one of many technical opportunities that remains underutilized due to systemic barriers.

The qualitative exploration of circularity policies and stakeholders provides insights into the missing regulatory and market drivers as well as the challenges to circularity that could enable SCM integration at scale. However, the question remains if this practice is truly circular and if it has a regenerative potential due to the extractive nature of the underlying process that produces those SCMs.

Together, they create a closed-loop perspective, showing that material-level innovations need policy and systemic support to be effectively implemented, just like any other aspects and practices of circularity.

The flexibility of the qualitative research allowed the addition of "*new pieces to the puzzle*" [39] while gathering and then analyzing the data, which by its turn allowed the inquiry to exceed the material-level drawn by the connection of the experimental part related to the SCM element in the research , and into general circularity practices in the built environment in a holistic manner.

1.7 Research novelty

With the significance, the objectives, and the outline of the research presented, the novelty aspect of research become clearer.

In project CO2REDRES, two main aspects are new contributions to science. The first is the study of such a number of SCM that have never been tested before or incorporated in pastes and mortars, which opens the door to knowing their properties and mapping the available products in the Greater Region that have potential for further development with all the benefits that this brings. The second is the use of the datasets that were generated to create a framework for a pozzolanicity index that is further discussed in the research results presented in chapter 4.

In project CO2REDSAP, also two main aspects can be considered. The first is the interdisciplinary nature of such a connection between the material and the policy and stakeholders part, that has not been done for the Luxembourg circularity ecosystem. The second is the framework building and the posterior analysis of interview data through the lenses of different ontologies applied to circularity in the built environment that is detailed further in the methodological considerations in chapter 5.

1.8 Publications

1.8.1 Article manuscript I: Experimental evaluation of the pozzolanic potential of calcined gravel wash muds from the Greater Region

Authors: Kaassamani, Sinan; Tokareva, Anna; Waldmann, Danièle

Journal: Not submitted

This thesis author's contribution to this paper refers to the methods, literature, experiments, and writing, and are mostly revolving around the empirical contributions with novel experimental results of new materials using existing methods of evaluation. The methods and results of this paper are discussed in depth in Part II, Chapters 3 and 4 of this monograph.

Abstract

The race to meet the challenges of reducing carbon emissions and working a step closer towards the United Nations sustainability development goals is bringing industry and academia together to research ways to address pressing issues in the construction industry. With a high carbon footprint, the production of 1 ton of Ordinary Portland Cement (OPC) roughly emits 1 ton of carbon dioxide into the atmosphere. In the pursuit of designing a more sustainable mix, the research team in this article studies 8 samples of different Gravel Wash Mud (GWM) for the use as Supplementary Cementitious Materials (SCM). The samples studied were collected from the Greater Region (Luxembourg, France, Belgium and Germany) and originate from different gravel mines in this area as waste of their industrial process. These fine clay-based materials are good precursors, rich in silica and alumina, that often enhance some concrete properties such as compression strength and resistance to alkali-silica reactions among others, all while reducing the amount of cement used and contributing to circularity by revalorizing waste materials and avoiding deposits in landfills. To activate these materials, they were thermally treated by calcination at different temperatures at 650,

750 and 850°C, then mechanically crushed into fine powders that were then used to substitute 20% of cement in pastes and mortars. The aim of this research was to assess the feasibility of using such materials as additions on an industrial scale. To this end, a chemical and mineralogical characterization of the powders were performed using X-ray fluorescence and X-ray diffractometry. Thermogravimetric analyses were performed to discover the behavior of the samples under heating. Other physical properties were researched such as fineness, granulometry and density. The pozzolanic activity was measured using Frattini and Chapelle methods, and compression strength tests were performed on prisms at 7, 28, 56 and 90 days for both mortars and pastes. The results showed a promising potential for some materials in which a 20% substitution of cement showed an increase of up to 10% in compression strength when compared to the reference.

1.8.2 Article II: Fine demolition wastes as Supplementary cementitious materials for CO2 reduced cement production

Authors: Tokareva, Anna; Kaassamani, Sinan; Waldmann, Danièle

Journal: Construction and Building Materials

This thesis author's contribution to this paper refers to the methods and experimental setting, and partially data analysis. The results of this paper are not discussed in depth in this monograph but are partially related to the literature review section 2.1 and the methods chapter 3 in Part II as they are intersectional with the research of project CO2REDRES

Abstract

Construction and demolition waste accounts for a significant amount of the total solid waste produced worldwide, and its recycling is challenging. Although some demolition waste is processed into recycled sand and rubble, the finer fractions resulting from screening and washing of recycled aggregates are not used. This research investigates the potential of use of real demolition wastes, namely concrete screening fines (CS), mixed concrete-ceramic screening fines (MS), and mud from recycled aggregates washing (WM), as supplementary cementitious materials (SCMs) in eco-efficient blended cement. The study employed various experimental methods, such as isothermal calorimetry, thermogravimetric analysis (TGA), and setting time tests, to evaluate the hydraulic activity of waste materials and the Chapelle test and TGA to assess their pozzolanic activity. The mechanical properties and microstructure of mortars containing 20% of waste powders were evaluated using compressive strength tests and scanning electron microscopy (SEM). The results showed that thermal treatment of waste materials at 500 °C improved the mechanical properties of mortars, increasing Strength Activity Index (SAI) by 10% for CS and MS and by 6% for WM after 90 days of curing. All three waste types achieved similar mechanical properties, with compressive strengths of at least 37.93 MPa, 46.25 MPa, and 51.33 MPa after 7, 28, and 90 days of curing, respectively. The contribution of waste powders to mortar strength was due to filler effect and partially dehydrated C-S-H products. However, pozzolanic ceramic inclusions in waste powders did not affect mortar strength at a 20% substitution rate. Therefore, the research findings indicate that waste materials derived from demolition can potentially be used as environmentally friendly materials in construction. Their use as SCMs with a substitution rate of 20% can reduce the CO2 emissions of cement production by at least 10.7%.

1.8.3 Article III: Using ceramic demolition wastes for CO2-reduced cement production

Authors: Tokareva, Anna; Kaassamani, Sinan; Waldmann, Danièle

Journal: Construction and Building Materials

This thesis author's contribution to this paper refers to the methods and experimental setting. The results of this paper are not discussed in depth in this monograph but are partially related to the literature review section 2.1 and the methods chapter 3 in Part II as they are intersectional with the research of project CO2REDRES and a continuation to the previous research.

Abstract

This study focuses on assessing the pozzolanic potential of two types of ceramic demolition waste, namely terracotta roof tiles and sanitary porcelain, as substitutes for traditional calcined clays in blended and limestone calcined clay (LC3) cement production. Experimental methods employed include the modified Chapelle test and XRD for pozzolanic activity evaluation, flexural and compressive strength tests, capillary absorption measurements, and SEM for microstructure analysis. Mortars containing 10%, 20%, and 30% ceramic powders and 5%, 10%, or 15% limestone filler were tested. The findings showed that porcelain powders exhibited lower pozzolanic activity due to their lower surface area and higher firing temperature of the material. Up to 20% substitution of OPC with terracotta had minimal strength impact, with a 103% strength activity index (SAI) at 90

days. Ultrafine terracotta powder showed promise in LC3 production with up to 30% OPC substitution, achieving a 97% SAI after 90 days. The poor mechanical properties of porcelain-containing mortars were explained by surfactants present in sanitary porcelain. This research informs the cement and processing industries on the potential use of specific ceramic demolition waste materials in eco-cement production, offering insights into blended pozzolanic cements and LC3 formulations, with the goal of reducing the carbon footprint of cement manufacturing.

1.9 Overview of the thesis structure

The thesis monograph is structured to comprehensively address the interdisciplinary nature of the research, integrating both quantitative and qualitative approaches discussed earlier as a main point in enriching the outcomes of both projects and weaving their interaction in multiple instances where applicable. It starts with this Introduction chapter that outlines the research problem, objectives, and significance, providing a roadmap for the study that gives a first idea on the content explored in the coming chapters. Following this, two Literature Review chapters delve into the theoretical and empirical foundations, with the first focusing on the quantitative aspects of the research related to the cement industry all the way from the manufacturing of raw materials to the in-depth literature on pozzolanicity and SCM including topics like concrete and cement sustainability in the end as transition to the second part addressing the qualitative dimensions of the research related to circular economy in the built environment on a wider level that encompasses more than material technology for reasons of completeness and offering a holistic view rather than focusing just on material circularity that might be a limiting factor to the richness of detail and input that a qualitative research path can offer. The subsequent chapters are dedicated to the Methodology, with one detailing the quantitative methods employed for project CO2REDRES—such as data collection, and analysis techniques with in-detail description of the experimental procedures, and experiment design — and the other elaborating on the qualitative methodologies in project CO2REDSAP, including interview design, analysis, ethical considerations and a critical reflection on the research process. Each methodology chapter is followed by a respective Data Presentation and Analysis chapter, presenting and interpreting findings within the context of the specified approach, linking back to the research questions defined in the beginning and preparing the stage for the discussion to follow. The thesis culminates in a Discussion chapter that synthesizes insights from both strands of research, highlighting their intersections and implications. This chapter emphasizes anew the value of an interdisciplinary approach, demonstrating how the integration of quantitative and qualitative methods enriches the understanding of the research topic and contributes to the broader field of study. In the discussion chapter the connection between material, policy, and stakeholder elements is revisited after having presented the results in the preceding chapters and a deeper dive not the analysis is discussed by revealing the patterns emerging from the earlier results and connecting those to the conceptual framework discussed in the methodology chapter of project CO2REDSAP. Furthermore, the discussion chapter brings in reflections on circularity in the built environment supported by quotes from the interviews that address questions broader than the research itself and the topic of materials, stakeholders and policy, before presenting the possible research limitations and transitioning into the conclusion. The last chapter, which is the Conclusion, presents a summary of the key findings and their significance for the research as well as the contributions to the field of both projects CO2REDRES and CO2REDSAP, and suggestions for future research. Posteriorly, the relevant annexes and references are included.

This page intentionally left blank

2 Literature Review

2.1 Review of relevant literature for project CO2REDRES

This section gathers the relevant literature on the material technology part of this thesis with a thorough review on OPC and SCMs starting at a the basic level of concrete history and cement manufacturing and moving on to the more complex concepts of hydration reactions, pozzolanicity, and clay activation among others that are relevant for this work and the posterior experimental methodology and data analyses in Part II, chapters 3 and 4 respectively.

2.1.1 A brief historical development of concrete as a construction material.

Among all the different materials naturally available for construction, quite a select few became as important to the core industry of building materials since humans started building up their inhabited environments. Important aspects such as durability, thermal and mechanical behavior, and strength and resistance were and are still important parameters that the choice of a material takes into consideration [40].

Classical building materials such as fire clay, stone, concrete, glass, wood, metals, bricks, polymers, and tiles, among other materials are widely used in Civil Engineering projects and have been the subject of a lot of research which has led over time to a significant improvement of their natural characteristics [41].

Concrete is one of the prominent materials in construction and has been in existence for thousands of years and in varying forms. The oldest concrete ever discovered dates back around 7000 BC and was prepared by mixing burned limestone with water and stone and left to set [42]. Its long history and versatility gave it a good advantage in the race for being the most consumed resource on earth with an incredible 7.3 billion cubic meters poured every year [43].

Centuries preceding the advent of modern concrete, ancient civilizations such as the Egyptians and Greeks employed a lime-based material as a base to their concrete. This practice eventually reached the Romans and spread to mass scale around 200 BC [44]. The Romans, in their exploration, stumbled upon a volcanic material possessing cementing properties, known as Pozzolanic cement [45]. Remarkably, this is the very cement utilized in the construction of iconic structures like the

Pantheon and Colosseum that still stand today. It wouldn't be until over a millennium after, that such big spans would be surpassed by the adoption of reinforced concrete, i.e. concrete with steel [45]. The Pantheon with a 43.3 m diameter concrete dome is over 2000 years old and still the worlds largest non-reinforced concrete dome.

The evolution continued, and it wasn't until the early 19th century that Joseph Aspdin made a groundbreaking contribution by patenting Portland cement [46]. This particular formulation marks a significant historical milestone as it closely resembles the foundation of the concrete we produce and utilize in contemporary times.

Since then, humans have been pushing concrete to the edge of its versatility, strength, and resistance, building beautiful structures that defy gravity ever more and span over land and water in the form of bridges, buildings, canals, dams, and other essential infrastructure for human life providing services, shelter and social function.

2.1.2 Cement

Originally form the 13th century word *caementa* in Latin, meaning stone chips used for making mortar, cement is a fine grey powder that exists in multiple blends and is mostly made of calcium, silicon, and aluminum [47], and is ultimately what creates together with water a binder paste that functions as a glue to bind together other particles such as sand and gravel, also known as aggregates, to form the hardened paste called concrete.

2.1.2.1 The industrial and manufacturing process

Portland cement manufacturing involves heating a raw mixture of limestone and clay to about 1450°C, followed by grinding the cooled clinker with 5% gypsum rock and 5% of another minor constituent, typically limestone [48]. The fabrication of cement is essentially a chemical process with close control of the principal oxides and the impurities present, both of which have an influence on the manufacturing process and the cement properties [49]. Usually, the production occurs in a three-stage process (see Figure 4) divided into raw materials preparation (steps 1 to 3), clinker production (steps 4 to 7), and clinker grinding (steps 8 to10). Although other configurations of manufacturing can exist, most industrial practices are similar to that presented in this section. One major difference can be the use of the wet process where a slurry is fed to the kiln, but it is less used nowadays due to energy efficiency reasons.

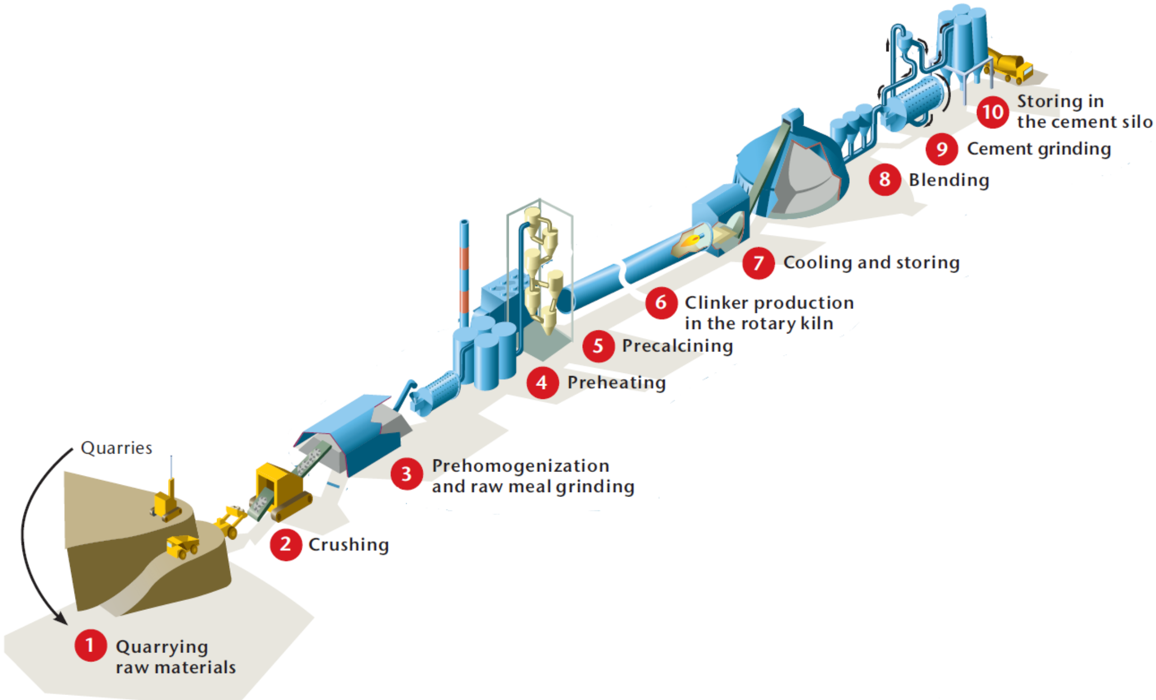


Figure 4. The general dry process of cement manufacturing adapted [49].

Stage 1: Raw materials preparation

The sources for cement production come from calcareous deposits (step 1), such as limestone, marl, or chalk, and are responsible for providing calcium carbonate, which is a key ingredient for cement [49]. The materials are usually extracted from natural deposits after the overburden layer has been removed, then go through a primary crusher into a vibrating screen that subsequently transports the crushed material to a secondary crusher [50]. Additionally, small quantities of other substances such as iron ore, bauxite, shale, clay, or sand may be added to supplement the raw mix with essential components like iron oxide, alumina, and silica, meeting specific process and product quality criteria.

In a subsequent step, the materials are transported to the cement plant where they are further grinded (step 2) and prepared for the rest of the process by mixing and milling (step 3) to achieve the desired chemical composition and produce a fine powder that will be fed in the next stage to the kiln. This is known as the raw meal.

Stage 2: Clinker production

This comprises the preheating and co-processing of other materials (step 4) [49]. In plants that contain a precalciner, the raw meal is heated up (step 5) and then directed towards it. Inside the preclaciner (also called the preheater) is where calcination starts to happen – calcination is the decomposition of limestone into lime and CO_2 after the bound water is evaporated. This reaction is what typically emits 60-70% of the total carbon emissions of the process, and the rest is generated from the fuel combustion for the energy source. The precalciner typically provides about 40% calcination [50].

The precalcined meal coming out of the precalciner heads to the rotary kiln (step 6) where a flame maintains a temperature of around 1450°C [49]. At this point, and before entering the kiln, the raw mix is still in powder form since it has not yet reached its melting point temperature. In some installations a flash furnace is embedded that provides a further calcination of up to 85 to 95% of the feed [50]. The intense heat of the kiln and the chemical and physical reactions melt the feed inside into what we know as clinker. At this stage the rest of the calcination happens.

After the clinker exits the kiln, it is cooled (step 7) from over a 1000°C to 100°C rapidly on a grate cooler and posteriorly stored for later use [49]. Subsequently, the processes of blending and grinding happen (steps 8 and 9) where the clinker is typically mixed with gypsum which helps in controlling the setting time of concrete [51]. Other materials are also added at this stage such as supplementary cementitious materials that create blended cements. The grinding process then gives the final grey powder known as Portland cement (PC). The cement is then homogenized and stored in silos, ready to be packed and commercialized [49].

The importance of understanding this whole process lies mainly in the amount of emissions that it generates in concrete's life cycle as a construction material and the usefulness of the industrial method when thinking of the adaptations needed to fit in an SCM production unit, or simply to incorporate such additions to regular PC.

2.1.2.2 The chemistry

The clinkering reactions that take place inside the kiln produce the mineral compounds described in Table 3 that constitute the quasi totality of the clinker portion of PC before the final additions. Figure 5 shows the sequence of reactions that take place in the kiln at different temperatures and the resulting mineralogical compounds formed at each phase. The reaction requiring the greatest amount of energy is the decarbonation of $CaCO_3$ at the range of 700 to 1000°C. After it is complete at around 1100°C lime reacts with silica to form C_2S. Until around 1250°C the level of unreacted lime stays high and this represents the lower limit of thermodynamic stability of C_3S. Melting occurs at around 1300°C, and this is phase where the mix is provided by the alumina and iron oxide present. Furthermore, the level of unreacted lime reduces as C_2S is converted to C_3S and is stabilized below 3% [52]. At 1450°C the formations are practically complete and the molten clinker will crystallize into its final mineralogical phases explained in this section.

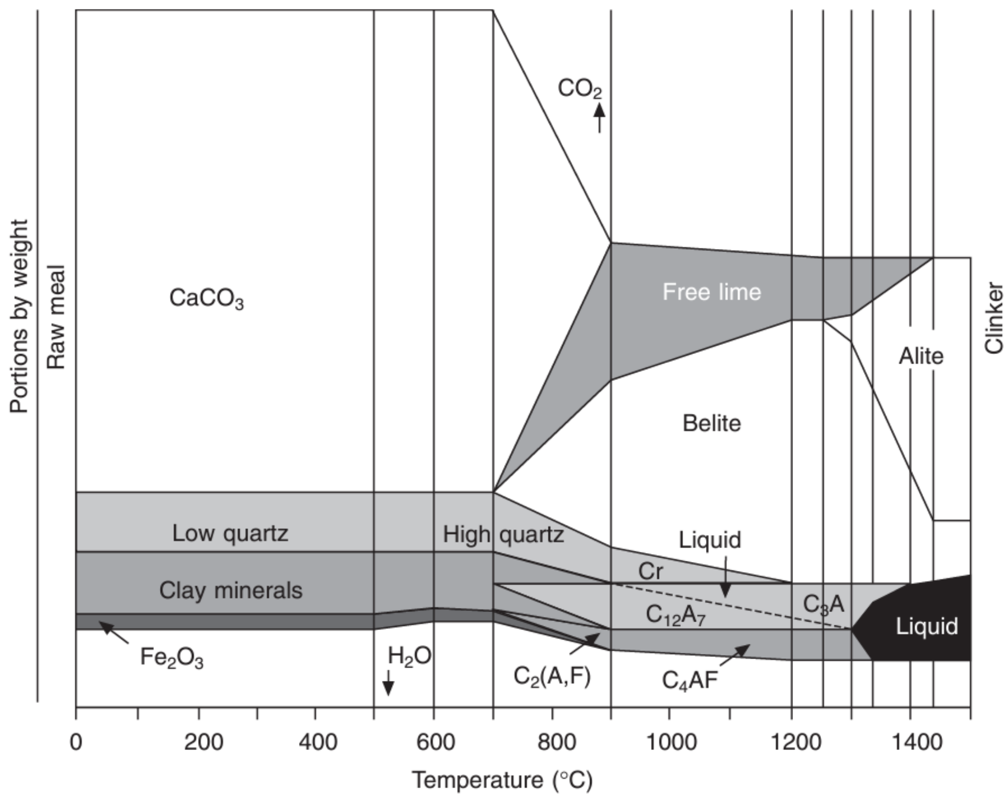


Figure 5. Sequence of reactions and mineral compound formations during the calcination of the raw feed across the temperature range [52].

Chemical analyses show that PC is majorly composed of four oxides (see Table 2): CaO (lime), SiO_2 (silica), Al_2O_3 (alumina), and Fe_2O_3 (iron oxide) [52] that constitute up to 95% of its entirety [53]. These oxides are usually denoted in scientific literature with the shorthand form as C, S, A and F respectively.

Table 2. The chemical composition in % weight of OPC, adapted [53].

Components	Chemical notation	Shorthand notation	Percentages *(approx.)*
Lime	CaO	C	64
Silica	SiO_2	S	22
Alumina	Al_2O_3	A	5
Iron Oxide	Fe_2O_3	F	3
Magnesia	MgO	M	2
Minor constituents	-	-	4
Total			100

These components form the mineral compounds existing in PC which are present in different proportions and affect the properties of cement directly.

Table 3. Ranges and nomenclature of main minerals present in OPC. Adapted [52].

Chemical name	Shorthand nomenclature	Chemical formula	Mineral name	Typical level (wt %)	Typical range (wt %)
Tricalcium Silicate	C_3S	$3CaO{\cdot}SiO_2$	Alite	57	45–65
Dicalcium Silicate	C_2S	$2CaO{\cdot}SiO_2$	Belite	16	10–30
Tricalcium Aluminate	C_3A	$3CaO{\cdot}Al_2O_3$	Aluminate	9	5–12
Tetracalcium Aluminoferrite	C_4AF	$4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$	Ferrite	10	6–12

Alite - Tricalcium Silicate (C_3S)

Alite is the most abundant mineral in PC as it occupies 45 to 65 wt% of cement, and it is also the most important mineral since it reacts at early stages of hydration to give strength to the cement paste. It can have different crystal structures depending on the temperature at which it was formed during the calcination process, but this does not lead to important differences in reactivity. Due to its crystal arrangement structure in which voids are present between the ions in the crystal lattice, it has a high internal energy which makes it highly reactive. The C_3S that forms in a cement clinker contains about

3-4% of oxides other than CaO and SiO_2. It would contain about 1 wt% each of MgO, Al_2O_3, and Fe_2O_3, along with even smaller amounts of other compounds such as Na_2O, K_2O, P_2O_5, and SO_3. The effect of the impurities is to "stabilize" the monoclinic structure avoiding the transition to a triclinic structure upon cooling [51]. Since it hardens quickly, the quantity of alite influences mostly two parameters: early strength and setting time.

Belite - Dicalcium Silicate (C_2S)

Dicalcium silicate, generally in the β-form, is the other main silicate component of PC. It has five polymorphs (α, α', β, γ and γ'-C_2S) out of which only β-C_2S is stabilized by the presence of impurities in cement and is commonly known as belite. It also has an irregular crystal structure but much less that that of alite, which gives it the lower reactivity characteristic [54].

Belite is the second most abundant compound in PC, typically constituting up to 20 to 40 wt% of the total compounds. It develops strength slower than alite when hydrated, so it consequently produces less heat upon hydration when compared to alite. This makes it an important component of cements where heat control is desirable [55].

Tricalcium Aluminate (C_3A)

The proportion of C_3A in PC, also known as the most reactive clinker phase of PC [56], is usually anywhere between 0 and 14 wt%. Just like C_3S, it has high reactivity due to the cavities in its crystalline composition matrix and undergoes an exothermic reaction during cement hydration, therefore generating a lot of heat during the first few days. To slow down the rate of hydration of C_3A and prevent a rapid setting gypsum is added to the cement mix in the last stage of the fabrication process while blending [55].

Due to its high reactivity, it influences early strength and the water demand in the cement. As a result, the more C_3A content, the higher the early strength, the higher the water demand in, and the lower the final strength in the cement paste matrix.

Tetracalcium Aluminoferrite (C_4AF)

This fourth major clinker phase is a stable compound with a composition mix between C_2A and C_2F and is formed because of the materials that are added during the manufacturing process to lower the temperatures required in the calcination kiln [55], its percentage is kept low from 1 to 2 wt%. The crystal structure of C_4AF is complex, as well as its hydration process and products. The actual composition of

C_4AF in cement clinker is generally higher in aluminum than in iron [57]. The C_4AF is the compound that is responsible for giving cement its known grey color.

2.1.2.3 The reactions

2.1.2.3.1 The hydration reaction

The hydration of PC is a sequence of overlapping reactions between the clinker compounds, calcium sulfate and water, that will change the paste from a fluid to a rigid state [58]. The stiffening process is called setting, and the strength evolution build up with the hardening of the cement paste in mortar and concrete. In its simplest form, the general hydration reaction can be described by:

Equation 1: the hydration reaction of PC.

$$cement + H_2O \rightarrow C - S - H + CH + \Delta H$$

Where CH represents calcium hydroxide and ΔH the amount of heat generated during the exothermic reaction.

The hydrated phases of PC presented in Table 4 are the product of the reaction of the anhydrous calcium silicate and aluminate phases present in PC with water that is known as the hydration reaction. The main clinker phases previously discussed in section 2.1.2.2 are the ones whose hydrated phases will be detailed in this section.

Table 4: Composition and characteristics of hardened cement paste per hydrated phase component (Type I PC, w/c ratio 0.5). [59]

Component	Approximate volume %	Other characteristics
C-S-H	50	Amorphous with microporosity
CH	12	Crystalline structure
AFm (hydration products of C_3A / C_4AF)	13	Crystalline structure
Unreacted cement	5	Hydration dependent
Capillary pores	20	w/c ratio dependent

2.1.2.3.2 The hydration of the silicates: tricalcium silicate and dicalcium silicate

Tricalcium silicate is the most important constituent of PC and its hydration controls the setting and early strength development of PC pastes, mortars and concretes. Its hydration produces the calcium silicate hydrate (C-S-H) which is an amorphous phase of variable composition that plays an essential role in strength development. The general C-S-H notation used does not indicate a specific stoichiometry. Dicalcium silicate hydrates in the same manner albeit at a slower rate than tricalcium silicate, contributing to a slower strength development. This difference in reaction speed is mainly due to the presence of O^{2-} ions in the C_3S structure [59].

The hydration of the silicates, on top of producing the C-S-H phase, forms portlandite, which consists of calcium hydroxide crystals. Calcium hydroxide ($Ca(OH)_2$) has a smaller crystal size and does not contribute as much as C-S-H to the strength of the hardened paste. However, it is found to be beneficial against shrinkage through acting as a restricting component when calcium silicate hydrates start to shrink. The hydration reactions of C3S and C2S are described in Equation 2 and Equation 3 respectively [60]:

Equation 2: Hydration reaction of C_3S

$$2(3\,CaO\,.\,SiO_2) + 6H_2O \rightarrow 3CaO \cdot 2\,SiO_2 \cdot 3H_2O + 3\,Ca(OH)_2$$

$$C_3S \rightarrow C - S - H + CH$$

Equation 3: Hydration reaction of C_2S

$$2(2\,CaO\,.\,SiO_2) + 5H_2O \rightarrow 3CaO \cdot 2\,SiO_2 \cdot 4H_2O + Ca(OH)_2$$

$$C_2S \rightarrow C - S - H + CH$$

2.1.2.3.3 The hydration of the aluminates: tricalcium aluminate and tertracalcium aluminoferrite

When the highly soluble tricalcium aluminate gets in contact with water, its initial high reactivity subsides and is succeeded by an interval of slow reactivity, before it picks up again after the initial hydration products called hexagonal hydrates (C_4AH_{13} and C_2AH_8) covering the C_3A surface are converted into cubic hydrates (C_3AH_6) which disrupt the barrier created by the latter. In the presence of gypsum, one of the additions to clinker in PC, the hydration reaction of C_3A is delayed by the formation of sulfoaluminate hydrates, also known as ettringite, that coat the surface of its particles.

This happens by impeding the diffusion of SO_4^{2-}, OH^-, and Ca^{2+} ions. Once the liquid phase of the hydrating system develops into a deficient state in SO_4^{2-} and Ca^{2+} ions, the protective coat is disrupted and the renewed hydration process of C_3A forms the aluminoferrite monosulphate hydrate (AFm phase) as a hydration product. The other hydration product being the aluminoferrite trisulphate hydrate (AFt phase), both amorphous layers.

The reaction of the ferrite minerals happens in an analogous manner, except that some portion of the aluminates in the hydrates are substituted by the ferrite minerals. Finally, the system reacts differently in the absence or presence of sulphates and different aluminate hydrates are formed: monsulfoaluminates in the case of poor sulfate and rich calcium conditions, and ettringite in rich sulfate environments [59]. The full equations of the hydration of the aluminates are shown below in full and simplified notation [60]:

Equation 4: Hydration reaction of C_3A

$$Ca_3Al_2O_6 + 3CaSO_4 \bullet 2H_2O + 26H_2O \rightarrow Ca_6Al_2(SO_4)_3\,(OH)_{12} \bullet 26H_2O$$

$$C_3A \rightarrow AFt$$

Equation 5: Hydration reaction of C_3A

$$2Ca_3Al_2O_6 + Ca_6Al_2(SO_4)_3\,(OH)_{12} \bullet 26H_2O + 4H_2O \rightarrow 3Ca_4Al_2(OH)_{12}\,SO_4 \bullet 6H_2O$$

$$C_3A + AFt \rightarrow AFm$$

Equation 6: Hydration reaction of C_3A

$$Ca_3Al_2O_6 + 6H_2O \rightarrow 3CaO_3 \bullet Al_2O_3 \bullet 6H_2O$$

$$C_3A \rightarrow C - A - H$$

Equation 7: Hydration reaction of C_4AF

$$Ca_4Al_2Fe_2O_{10} + 7H_2O \rightarrow 3CaO \bullet Al_2O_3 \bullet 6H_2O + CaO \bullet Fe_2O_3 \bullet H_2O$$

$$C_4AF \rightarrow C - A - H$$

2.1.2.3.4 The hydration of ordinary Portland cement

While looking at the clinker compounds separately is an important step to understand what each mineral brings into the hydration reaction, all those compounds undergo the reaction simultaneously and jointly in the case of PC. Table 5 summarizes the main hydration stages in concrete mixtures and gives an explanation on the chemical and physical changes that happen at each of the stages described. Certain authors divide the phases differently including a steady phase at the end of the end summing up to 5 phases in total [61]. The steady phase is the one where a so-called "skeleton" is formed by all the hardened hydration products where the maximum strength has been reached.

Table 5: A summary of the four main hydration stages of PC concrete, adapted [59].

Processing stage (in concrete)	Chemical process	Physical process	Relevance to physical properties of concrete
Initial phase / first few minutes (wetting and mixing)	Rapid dissolution of free lime; Superficial hydration of C_3S; Immediate formation of AFt; Gypsum or syngenite can form.	High heat generation mostly from the dissolution of aluminate phases, plus some alite and CaO.	Rapid formation of aluminate hydrates, plus gypsum and syngenite influences rheology and may affect the subsequent microstructure.
Induction period (transport, placing, finishing)	Nucleation of C-S-H; Rapid decrease in SiO_2 and Al_2O_3 to low levels; CH become super saturated and portlandite nucleates.	Low heat evolution rate, and an increase in viscosity due to the slow formation of C-S-H and more AFt in the absence of admixtures.	The formation of C-S-H leads to setting, and continuous formation of AFt and AFm phases can influence workability.
Acceleration period (setting and early hardening)	Hydration of C_3S into C-S-H and portlandite accelerates to reach maximum; CH supersaturation decreases.	High rate of heat evolution; hydrates forming rapidly leading to solidification and decrease in porosity.	Setting (initial and final set) of the paste (from plastic to rigid consistency); the stage at which early strength develops.
Post-acceleration period (demoulding + continued hardening)	Rate of C-S-H and CH formation form hydration of C_3S and C_2S in deceleration; renewed hydration of aluminate phases to give mostly AFm phases. Formed AFt may redissolve and/or recrystallize.	Decrease in the rate of heat evolution and porosity. Particle to particle and paste to aggregate bond formation.	Continuous strength increase because of the decreasing porosity (at a diminishing rate). Hydration can continue for years as long as water is available – shrinkage happens due to drying.

The hydration reaction being an exothermal one, produces heat in the concrete. This heat is mostly influenced by the C_3S and C_3A content but can also be impacted by the fineness of the cement, the curing temperature, the geometry including thickness of the concrete layer, and the water to cement ratio as well [59]. The progress of the reactions described in Table 5, can be visualized in Figure 6 that shows the peaks of hydration associated with the main hydration products.

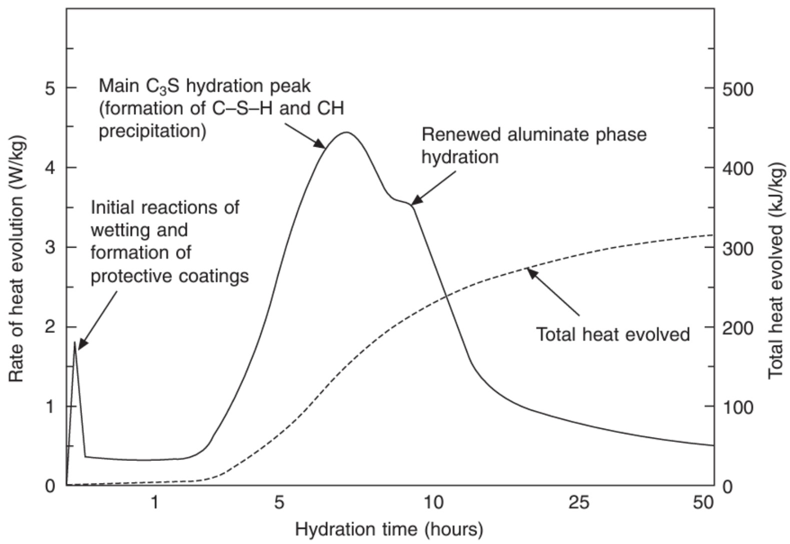


Figure 6. Heat of hydration of a cement paste measured by conduction calorimetry [52].

Another important aspect of hydration is how it influences the concrete microstructure, and in return is influenced by the raw materials used. Figure 7 shows a snapshot illustrating the hydration mechanism and its products at four different stages. At 15 minutes into the mixing process, some of the calcium sulfate begin to dissolve and ettringite is formed, this controls the hydration of C_3A and prevents its quick setting. As the cement paste starts to set the C-S-H gel is formed around the C_3A and C_3S particles, and the anhydrous material starts to be replaced. However coarser particles can still retain an unreacted core due to the surrounding C-S-H gel covering the entirety of its perimeter and preventing more water from seeping in.

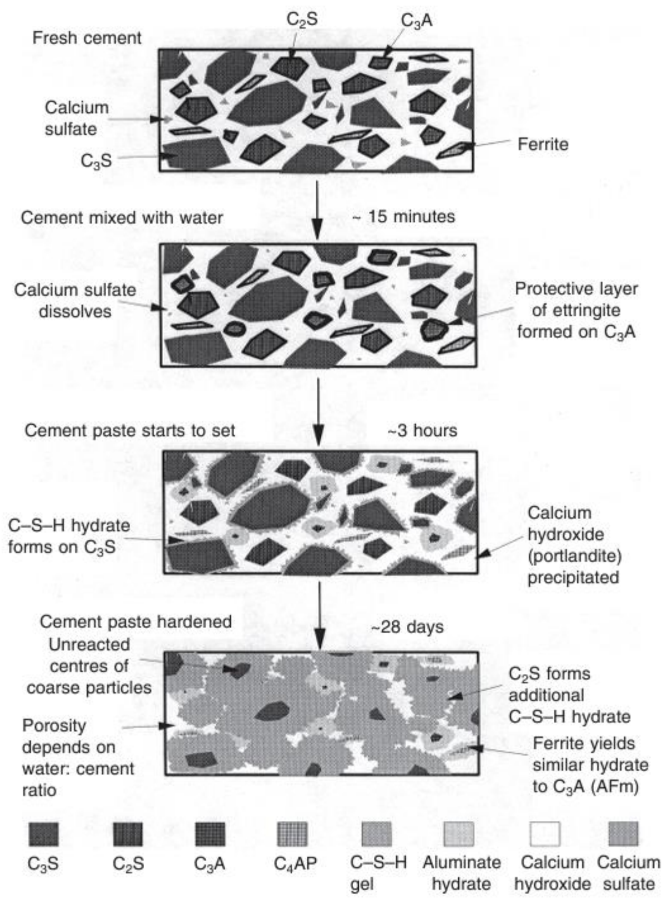


Figure 7: Illustration of the hydration of a cement paste at four different stages [52].

The 'outer hydration product' forms in areas that were initially saturated with water, as well as spaces taken up by smaller cement grains and the interstitial materials C_3A and C_4AF. Under an electron microscope, a cross section at this stage reveals crystals of calcium hydroxide Ca(OH)2, AFm/AFt, and C-S-H presenting a sheet like structure. The structure of the outer hydration product is important in strength development and significantly influenced by the paste porosity that is itself affected by the initial water-to-cement ratio[52].

The study and investigation of cement hydration kinetics is important, especially from a sustainability perspective. Efforts to create more eco-friendly concrete involve intricate mix designs incorporating secondary mineral additions, recycled aggregates, and various chemical admixtures. A thorough understanding of the fundamental hydration mechanisms is necessary for devising rational mixture proportions and effectively designing and selecting these additions, which in turn enhances the sustainability of concrete [62].

Furthermore, quantifying the amount of residual non-hydrated cement in hardened concrete or paste is crucial for assessing the potential of existing cement paste or mortar to be reused in new concrete, not merely as an inert aggregate but as an active supplementary SCM with cementing properties. Studies are currently lacking for this specific issue to research the practicality of such recovery. Certain estimates fall around the range of 6 to 36% where cement pastes with lower water to cement ratio showed a residual non-hydrated cement mostly in the form of alite and belite [63].

Another important feature is the presence of calcium hydroxide which is the main component to react with certain pozzolanic SCM silicates to form extra C-S-H phases to contribute to the strength of the cement paste matrix. Therefore, understanding the microstructure and the hydration mechanism and products are of extreme importance for such research endeavors, just as it is the case for project CO2REDRES.

2.1.2.4 Cement and sustainability

The sustainability question comes into scene as soon as PC concrete as a construction material is the subject. Since the production of concrete is very emission intensive, generating roughly 1t of carbon dioxide per ton of PC, it becomes important to find ways of using as little cement as possible in the context of using concrete as a building material in a sustainable way. In this setting, research has focused on many aspects of the cement-concrete conundrum at the techno-material level with solutions going towards lowering water/cement (w/c) ratio that is more sustainable than normal w/c concrete through the use of chemical additives, or increasing the strength of concrete through increased packing density i.e. the higher proximity of cement particles making the matrix denser and less porous and consequently using less materials for better outcome, as well as the role and importance of supplementary cementitious materials in making concrete more circular, and less clinker intensive by adding other materials, often industrial waste or by-products that lower the clinker content and contribute to a greener concrete [64].

In the last years, research has been focused on two trends: reducing the environmental impact of concrete, and continuous improvement of its performance. Additions, and substitutions to contents of PC included a huge variety of materials investigated such as calcined clays including metakaolin [65], industrial by-products such as fly ash [66] and ground granulated blast furnace slag [67], lime sludge waste from the paper industry [68], bottom-ash from the combustion of mineral coal [69], biosolids (raw), biochar (pyrolyzed) and bioash (calcined) originating from wastewater treatment facilities as partial cement replacement [70], and zero-cement concepts such as alkali-activated materials [71] and geopolymers synthesized from aluminosilicate materials with acid or alkaline binders [72], or some other concepts such as the Limestone Calcined Clay Cement (LC3) with a clinker percentage reduction of up to 50% already in industrial production and use [73].

In addition to the research on cement as a material and its substitutes, also aggregates in conventional PC concrete and mortar were the subjects of research and experimentations, for example with plastic wastes investigated for use as aggregates unsuccessfully on almost all properties except for shrinkage and abrasion wear [74], rubber from scrap tires for use in rubberized concrete to increase its ductility and ability to absorb energy while improving some concrete properties such as freeze-thaw and abrasion resistance although at the detriment of mechanical strength [75].

Another sustainability concern is that of the emissions and impact in the industrial process of cement manufacturing that ranges from ecosystem destruction by quarrying raw materials to all the energy intensive process of clinker production in the kiln. One pilot study on alternative energy use for a net-zero emission by proposing an innovative circular model concluded that it is feasible by adding to the production plant a three power-to-gas system: a CO_2 capture unit, water electrolysis for hydrogen and oxygen generation, and unit for synthetic natural gas production, all working in a closed loop system [76]. The EU together with The European Cement Association (CEMBUREAU) have both signaled that up to 42% of the carbon reductions would be achieved through carbon capture, use and storage [3].

As a wrap up to the sustainability question on cement, the carbon reduction levers raised in the low-carbon transition roadmap for the industry according to the International Energy Agency (IEA), lay in improving energy efficiency, switching to alternative fuels, reducing cement to clinker ratio, using emerging and innovative technologies, and alternative binding materials for cements [49]. All those ideas have been and continue to be researched and set in motion as demonstrated in this section.

In one way or another, all those ways of transforming cement as a construction material into a greener element or reducing impact and shifting towards a zero-emission in the industry have as a common denominator one or more components of circular economy strategy. Although this topic will be addressed in deeper detail in section 2.2. it is important to already establish the link in research between the empirical experimental aspect on studying sustainable cement blends with secondary raw materials and the theoretical conceptual one on how for different reasons this and other circular initiatives in the built environment are not widely implemented as one would expect them to be.

Linking back to the reactions, the next section of this literature review will introduce the pozzolanic reaction, which is important to understand how it also relates to sustainability through transforming calcium hydroxide naturally present in the hydrated phase into C-S-H content that would have a positive effect on strength development especially that it is achieved by adding other materials to PC, thus reducing the clinker to cement ratio.

2.1.2.5 The Pozzolanic effect

2.1.2.5.1 Pozzolanic materials

A pozzolan is defined by ASTM C125 [77] as *"a siliceous and aluminous material which, in itself, possesses little or no cementitious value but which will, in finely divided form in the presence of moisture, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties."*

According to EN 197-1:2000 pozzolanic materials that can be added as constituents of cement blends are natural substances (e.g., volcanic ash) of siliceous or silico-aluminous composition or a combination thereof [78]. However, these materials can also be artificially made from other naturally occurring materials, such as metakaolin, and industrial by products, such as fly ash and silica fume, after some thermal treatment and can be produced for this intended purpose or obtained as waste of a certain industrial process [79]. Pozzolanic materials are found in many locations all around the globe and come in various types with complex mineral compositions. The chemical composition of pozzolanic materials can vary significantly depending on their source but usually contain a high amount of silica SiO_2 and alumina Al_2O_3 [80].

2.1.2.5.2 Natural Pozzolans

Natural pozzolans are incoherent pyroclastic materials primarily composed of silica and alumina. Due to this composition, they have a strong affinity for lime and alkalis and are essentially vitreous in nature. They are characterized by finely divided, bubbly elements with large internal surface areas and are the fruit of explosive volcanic eruptions, where the rapid cooling of ejected molten magma preserves the material's glassy state. In contrast, effusive eruptions produce volcanic ashes that cool more slowly, resulting in fewer or no bubbly vitreous fragments (due to the absence of the interaction with explosion gases), making them less reactive with lime [81].

The natural pozzolans can be divided into two groups or categories. The first group, primarily constituted of volcanic dust and ash materials, and this relates to the origin of the term 'pozzolana' which is derived from the Roman source of zeolitic tuff at Pozzuoli at the base of Mount Vesuvius in today's Italy. Natural pozzolans are present all around the world in places such as the Santorin earth of Greece, and volcanic deposits of other places including the USA, Japan and New Zealand among others. The other group of natural pozzolans consists of diatomaceous earth, which is mainly composed of diatom fossil remains of opaline silica with the USA producing around 30 per cent of the world's total [82].

2.1.2.5.3 Artificial Pozzolans

As the name suggests the artificial pozzolans are materials that undergo an industrial process or occur as waste or by-products of another industrial process. The production of artificial pozzolans involves processes such as combustion, calcination, and grinding to create materials with high pozzolanic activity, which is crucial for improving the performance of blended cements [29]. Examples of artificial pozzolans include fly ash, calcined clays, ground granulated blast furnace slag, silica fume, and less common ones such as calcined shales, soils, rice husk ash etc. Some of those materials will be further detailed in section 2.1.3 under Supplementary Cementitious Materials (SCMs)

2.1.2.5.4 Mechanism during cement hydration: physical effects and the pozzolanic reaction

The role of pozzolanic materials in cement hydration can be divided into two categories: physical effects that mostly appear during the initial phase of hydration and the pozzolanic reaction effect that that becomes prominent in the later stages when CH from the hydration reaction is present in the hydrated cement matrix and continue to act well into the last phase described earlier in this section [60].

The physical effects obtained by adding pozzolanic materials to the cement mix can be summarized according to Lin et al. [60] by the following points:

a. *Filler effect*. This permits the finer particles of pozzolanic materials to serve as a filler between the cement particles, improving the packing density of the matrix and creating a denser interfacial transition zone (ITZ). In the study of concrete microstructure, the ITZ is defined as a cracked and porous area between the cement paste and the outermost fibers of coarse aggregates that is rich in CH crystals [83]. This is the weakest zone in concrete structure due to the lower presence of calcium silicate hydrates and the higher porosity when compared to other parts of the cement matrix [84].
b. *Ball-bearing effect*. Certain pozzolanic materials such as fly ash or other that have spherical forms can present the so-called ball-bearing effect, which reduces the interface friction between angular cement grains and increases the rheological properties of the fresh paste permitting greater workability for an equal water-binder ratio [60],[85].
c. *Dilution influence*. Certain pozzolanic materials can dilute the cementitious system, potentially reducing the early strength developed in the cementitious matrix, but this is balanced by the fact that less cement is needed to maintain the same water content thereby increasing the w/c ratio and enhancing the degree of cement hydration [60]. In other words, looping back to the filler effect, since/until the filler material does not generate hydrates, the higher water to clinker ratio creates more space for the hydration products of the clinker phase [86].
d. *Nucleation effect*. The particles of pozzolanic materials can act as heterogenous nucleation and crystallization sites for hydration products leading to a higher hydration degree [60]. Nucleation is part of the physiochemical effect of adding pozzolans to cement blends where the fine particle size distribution of the added materials, with their high contact surface area, can provide a better interfacial area for hydration reactions to occur – these known as nucleation sites. These sites can provide additional surfaces that help molecules involved in hydration to overcome the physical resistance or obstruction from the medium they are in by creating more and closer surface area(s) for the reaction.

2.1.2.5.5 The pozzolanic reaction

As described previously, the addition of pozzolans to PC allows for a partial substitution of clinker by those materials. The pozzolanic reaction happens when the silica and alumina present in these materials react with the calcium hydroxide present in the cement matrix [87]. As the cement hydrates, calcium hydroxide is released, then undergoes dissolution also through hydration liberating OH^- and Ca^{2+} ions. The OH^- concentration causes the medium's pH value to increase until approximately 12.5, which then creates the favorable conditions for the pozzolanic reactions to occur. In these reactions the Si and Al combine with the available Ca, developing as a product the cementitious compounds like those of the hydration reaction discussed in page 58 i.e., Calcium Silicate Hydrates in the case of Silica and Calcium Aluminate Hydrates in the case of Alumina. A simplified qualitative representation of these reactions is summarized in the equations that follow (Equation 8 to Equation 12) [60], [79], [87].

Equation 8: The hydration of Calcium Hydroxide

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$$

Equation 9: Simplified notation of the Silica pozzolanic reaction

$$Ca^{2+} + 2OH^- + SiO_2 \rightarrow C-S-H$$

Equation 10: Simplified notation of Alumina pozzolanic reaction

$$Ca^{2+} + 2OH^- + Al_2O_3 \rightarrow C-A-H$$

Equation 11: Pozzolanic reaction for Silica

$$3Ca(OH)_2 + 2SiO_2 \rightarrow 3CaO.2SiO_2.3H_2O$$

Equation 12: Pozzolanic reaction for Alumina

$$3Ca(OH)_2 + Al_2O_3 + 3H_2O \rightarrow 3CaO.Al_2O_3.6H_2O$$

Figure 8 illustrates the pozzolanic reaction (bottom sequence labeled as CS specimen) as compared to the simple hydration reaction of cement (top sequence labeled as C specimen) through a visual representation of initial hydration in the first column, the hydration reaction in the second, and the final compound formation in the third. The example is given with silica fume as the pozzolan and shows the formation of extra calcium silicate hydrates (in yellow) originating from the pozzolanic reaction having consumed a potion the portlandite present from the initial hydration products.

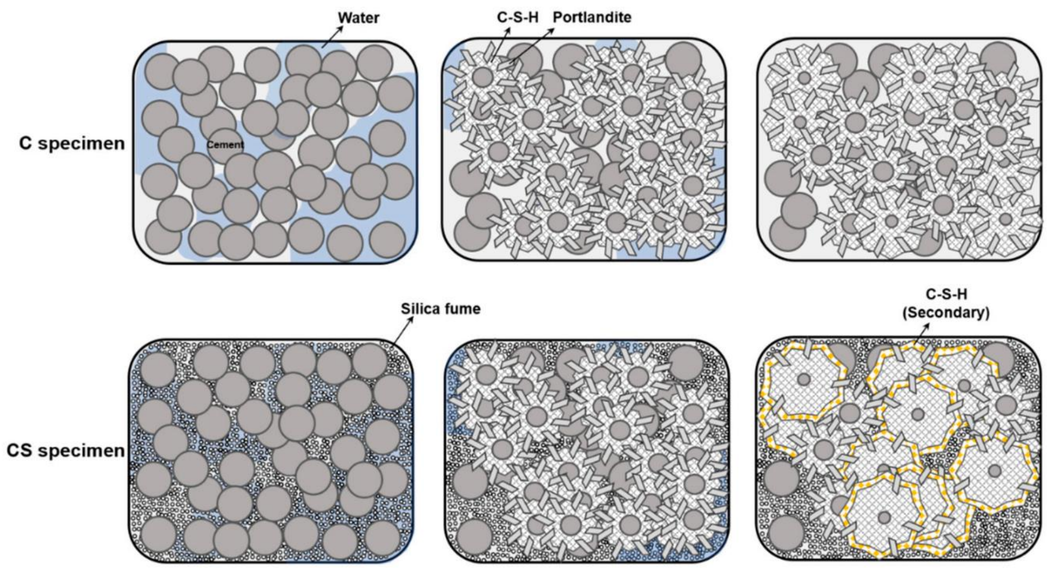


Figure 8: Schematic comparative representation of the phases of cement hydration (top) and pozzolanic reaction (bottom), adapted from [88].

While pozzolanic materials play a crucial role often improving one or more aspects such as durability, mechanical characteristics, and sulphate resistance in concrete, as well as reducing the calcium hydroxide content, the pozzolanic reaction can have an undesirable effect in case sulfates are abundantly present. Sulfates can occur in both industrial wastes and natural soils, this provoking the formation of ettringite, especially influenced by a high Ph, the presence of soluble sulfate, and availability of water. Ettringite is an expansive hydration product discussed previously in the hydration of C_3A and is detrimental to the health of concrete when it leads to cracking [80], [87].

2.1.2.5.6 Measuring pozzolanic activity of materials

As the kinetics of the Pozzolanic reaction have been established, it is obvious that the "successfulness" of a pozzolan is depending on the rate of the reaction, and this is related to the solubility of SiO_2 and Al_2O_3 [89] therefore to availably react with calcium hydroxide [90]. Various testing methods that either focus on the reaction or the final properties of the pozzolanic material addition have been used in the literature, some regulated through standards and other not. These tests are often classified as direct and indirect testing methods depending on their scope.

2.1.2.5.6.1 Direct testing methods for pozzolanicity measurement

The direct methods are the ones that use chemical measurement techniques to quantify the reduction of calcium hydroxide over a certain amount of time through classic laboratory experiments or more sophisticated technological approaches using mineralogical and thermogravimetric analyses.

Chapelle test

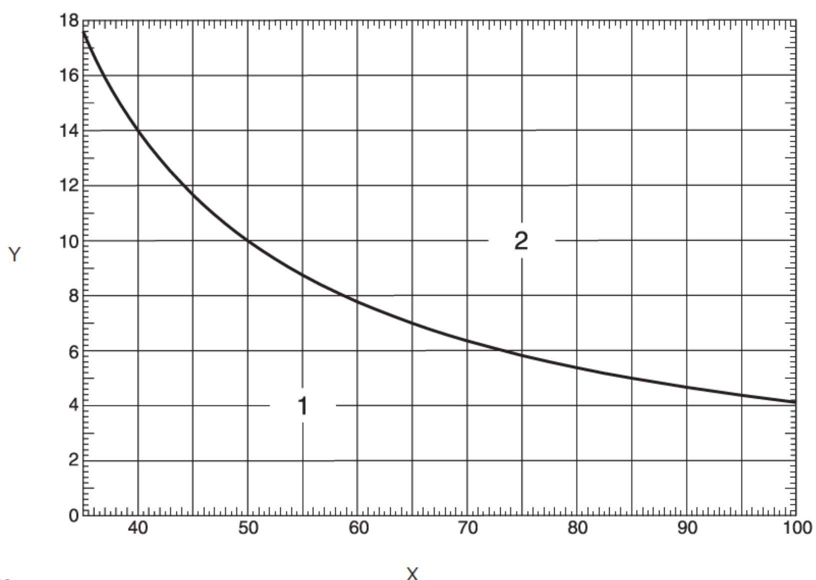
The Chapelle test is a technique used to determine the pozzolanic activity of materials (usually metakaolin) by measuring the ability of a pozzolan to react with calcium hydroxide $Ca(OH)_2$ under controlled conditions of time and temperature. The most commonly used procedure is the modified Chapelle which is described by the French norm NF P 18-53 [91], where a sample is prepared by weighing 1.0 g of calcined clay, blending with 2.0 g of pure CaO and adding 250ml of distilled water in a sealed flask that is then placed on a heated stirrer plate at 90°C, for a specific period of time, usually around 16 hours.

This simulates the pozzolanic reaction by accelerating the interaction between the pozzolan and the calcium hydroxide present in the solution. After the heating period, the mixture is cooled and filtered to separate the solid and liquid components. The remaining calcium hydroxide in the filtrate is determined by titration with a standard acid solution, such as hydrochloric acid (0.1 N HCl). The amount of calcium hydroxide that has reacted with the pozzolan is then calculated based on the difference between the initial and final amounts of calcium hydroxide.

The result is expressed as the amount of calcium hydroxide consumed by the pozzolan per unit weight of the pozzolan, usually in milligrams of $Ca(OH)_2$ per gram of pozzolan. A higher consumption of calcium hydroxide indicates higher pozzolanic activity. The Chapelle test provides a quick and practical way to evaluate the reactivity of pozzolanic materials [91], [92], [93], [94].

Frattini test

The Frattini procedure is defined by EN 196-5 [95], and consists of testing a sample solution of 20 grams with 20% substitution of the tested pozzolan mixed with 100ml of distilled water, i.e. 80% cement (CEM-I, without additions) and 20% of the tested pozzolan. Multiple studies researching pozzolanic activity such as [22], [28], [96], [97] use Frattini test as a reliable test. Unlike Chapelle test, the Frattini method tests the reaction of the pozzolan with cement, rather than the calcium ions coming from pure calcium oxide. The samples are prepared and mixed vigorously for 20 seconds until there are no lumps. The solutions are kept in flasks in a temperature enclosure (oven) with a uniform temperature at 40°C until the test das, 8 or 15 days for each sample. If the solution satisfies the test at 8 days then it is not necessary to continue to the 15th day. At the desired period, the solution is quickly (in less than 30s) filtered under vacuum through a Buchner funnel into a vacuum flask using dry double filter paper. Then the vacuum flask is sealed and let cool at room temperature. The filtrate is then used to determine the total alkalinity of the solution with 0.1 mol/l dilute hydrochloric acid to calculate the hydroxyl ion concentration OH^-. The same solution is then used to calculate the calcium oxide concentration after adjusting the pH to 12.5 and titrating with a 0.03mol/l EDTA solution until the end point. The results are then plotted onto the graph shown in Figure 9. The plot contains the curve ([CaO] = 350/([OH] -15)) of calcium ion saturation concentration. All the points plotted below the curve satisfy the test's verification the points, i.e. the tested material is considered pozzolanic, and vice-versa [95].



Key

1 Pass
2 Fail
X Hydroxyl ion concentration, mmol/l
Y Calcium ion concentration (expressed as calcium oxide), mmol/l

Figure 9. Graph diagram for assessment of pozzolanicity with Frattini test [95].

Lime consumption test

During the hydration of Portland cement, calcium hydroxide ($Ca(OH)_2$) precipitates as the mineral portlandite. When a pozzolan is present, it reacts with the $Ca(OH)_2$, causing more solid $Ca(OH)_2$ to dissolve until either the pozzolan or portlandite is depleted. The saturated lime test simplifies this process by using a fixed amount of $Ca(OH)_2$ in solution. In this test, 1 gram of pozzolan is added to a plastic bottle containing 75 ml of saturated lime solution, which is prepared by dissolving 2 grams of hydrated lime in 1 liter of distilled water. Like the Frattini test, the bottles are sealed and placed in an oven at 40°C for 1, 3, 7, and 28 days. After each period, the samples are filtered and titrated for hydroxide OH^- and calcium Ca^{2+} ions using the Frattini test procedure. Since the initial quantity of Ca^{2+} ions is precisely known and these ions only interact with the test material or water, the amount of lime fixed by the test materials can be quantified. Results are reported as mmol of CaO fixed or as a percentage of total CaO fixed per gram of pozzolan. Notably, portlandite's solubility decreases with increasing temperature, meaning some $Ca(OH)_2$ initially precipitates at 40°C before dissolving again to react with the pozzolan. However, the total amount of $Ca(OH)_2$ in the system remains constant, and the elevated temperature ensures a prompt reaction with the pozzolan [28], [96]. Some authors consider that the results are less reliable than other methods[96], while other prefer the method due to its simplicity.

Thermogravimetric analysis

A more sophisticated method technologically since it requires specialized lab machines, it consists in testing the consumption of calcium hydroxide in the cementitious matrix, just like the other direct methods. However, the preparation here is different since its not the ions in solutions that are measured but rather the loss of mass of a preprepared powder sample of a blended cement paste containing the pozzolan, hydrated and cured for typically 2 and 28 days. After curing, the samples have their hydration stopped, and are dried and grinded to form homogenous fine powders that can be analyzed using thermogravimetry Differential Thermal Analysis (TG-DTA). The mass of consumed calcium hydroxide is identified by the loss of mass between the temperatures of 400 and 550/600°C, the range at which the dehydroxilation of calcium hydroxide happens. The calcium hydroxide content in the paste is subsequently determined by subtracting the amount consumed in pozzolanic reactions from the amount produced during cement hydration. The pozzolanic activity is calculated by comparing the fixed calcium hydroxide in the sample with the amount consumed in the control. [98], [99], [100], [101].

Mineralogical analysis

Evidence of a pozzolanic reaction can be detected also through the mineralogical nature of the final hydration product by checking for evidence of additional hydration products and variation of calcium hydroxide content. This is usually achievable by means of an X-ray diffraction test (XRD), a nondestructive technique that reveals the crystallographic structure, chemical composition, and physical properties of a material The test is usually run on a powder sample of the crushed and finely grinded hardened paste and then the qualitative and or quantitative analysis is performed to assess the structure for evidence of the pozzolanic reaction, compared against a control sample. [80], [102], [103], [104]

2.1.2.5.6.2 Indirect testing methods for pozzolanicity measurement

As opposed to the previously exposed methods, the indirect ones measure changes in physical properties of the concrete hydrates including the pozzolanic material added. The indirect nomenclature is related to the fact that the calcium hydroxide consumption is not considered, but rather the overall effect that the addition has on certain properties of the system, such as strength development, or electrical conductivity. Results from indirect pozzolanic activity tests are frequently validated with direct tests to ensure that pozzolanic reactions are de facto taking place [28]. Often both direct and indirect methos are used to assess pozzolanicity and can end up drawing correlations the confirm the results through different tests.

Strength Activity Index (SAI)

This indirect method evaluates pozzolanicity through the compressive strength measurement of a specimen prepared with a percentage of pozzolan (usually up to 20% in the case of European and US codes, but some studies use higher substitution rates to compare) replacing the CEM-I class cement, compared to a control specimen made with 100% OPC, usually with a fixed w/c ratio of 0.5. The specimens take the shape of rectangular prisms where the paste or mortar mixture is molded and then de-molded after 24h then cured for 7 and 28 days, although many studies also use intermediary dates as well as longer periods since the pozzolanic reaction is known to continue until later stages. The replacement rates and the desired strengths vary from norm to norm, for example for ASTM C618 [105], an SAI greater than 0.75 after 7 and 28 days at a 20% cement replacement is considered as an indicator of pozzolanic activity. The SAI is calculated as the percentage strength relative to the control specimen. The compressive strength value is usually the average of three or more tests on unique specimens. This is one of the most used metrics, as it related to the main concern of strength development in concrete and is a reliable method to measure physical performance of hardened mortar, especially if it is to be used as a construction material and had a load bearing function [28], [96], [97], [104], [106].

Calorimetry

As other methods quantify the chemistry or structure of hydrated cement, calorimetry measures the rate of hydration by measuring thermal power, in other words the heat that is generated while the cementitious-pozzolanic matrix is developing its properties (see heat of hydration graph in Figure 6). By measuring the heat generation, any additional amount due to a pozzolanic reaction can be detected. The apparatus consists of a vial, sensors, and a heat source in a climatic chamber. In the isothermal calorimeter, the sample is placed in the vial that contacts a heat flow sensor. This sensor detects the heat transferred from the vial to a constant temperature heat sink. An inert reference sample with the same heat capacity as the actual sample is also measured. The calorimeter's output is therefore calculated as the difference between the heat flow signals of the sample and the reference in mW/g.[94], [100], [107]

Electrical conductivity test

This method of testing pozzolanic activity evaluates the direct reaction between the active components of the pozzolan represented by silica and alumina and the calcium hydroxide by monitoring the change of conductivity in the solution in which they are present. Variations of this test’s setup as well as the quantities used exist, however most tests consist in monitoring, at regular intervals of time, the electrical conductivity of 20 ml of saturated solution of calcium hydroxide at 40°C after 2 g of calcined clays are added to the solution. A low electrical resistance is associated with high calcium hydroxide consumption and vice versa. Therefore, the conductivity values gradually decrease with the time when the added material is reactive due to the consumption of ions by the pozzolanic reaction. [96], [108], [109]

Other tests

Other direct and indirect forms of testing exist but are either context dependent, not widely spread, or less reliable than the ones presented in this section. To name some, the acid/alkali dissolution method for example shows low accuracy and reproducibility, as well as being highly dependent on the pozzolan and reagent characteristics, or the bound water ratio method based on measuring relative weight loss in a pozzolan-cement system at a high temperature range from 100 to 1000°C over a 3 day period that may provoke changes to the structure of the material and fails to separate evaporable water [80].

2.1.3 Supplementary Cementitious Materials

The natural next step after understanding the mechanisms of cement hydration and pozzolanic reaction is to explore some of the promising materials that have been researched and utilized in recent years as partial or complete replacements for clinker-based cements. Supplementary Cementitious Materials (SCMs) fulfill this role by exhibiting properties comparable to Portland cement (PC) in various ways—chemically, physically, or through their capacity to form hydration products via hydraulic or pozzolanic activity, thus enabling effective substitution [110]. SCM is an umbrella term used to describe those inorganic materials. This section looks at some of the most used SCMs and their properties and effects as additions.

A wide variety of materials are being explored as SCMs, as the cement industry transitions to a more ecological pathway and classic existing materials such as fly ash and slag have seen their supply diminishing because of coal plant closures and a higher recycling effort in the steel industry. These materials still face the challenges of validation, resource limitations, and proper evaluation before widespread adoption [111].

The chemistry of SCMs is a very important part of the research that those have undergone, and various authors [86], [110], [112] have investigated the phases that generally characterize SCMs (Figure 10) and their hydrates (Figure 11). The key points illustrated are:

1. The chemical composition: CaO (calcium oxide), SiO_2 (silica), and Al_2O_3 (alumina) as the main compounds constituting SCMs. Some can be a mix of two or three such as slags containing limestone, silica and alumina, and others on the purer edge such as silica fume that is mostly constituted by silica and hence is closer to the top edge of the triangle. Metakaolin and other natural pozzolans, especially clay-based ones are rich in silica and alumina at the same time. It is worth to note that some SCM might even contain other residual compounds that are not considered major constitutional phases.

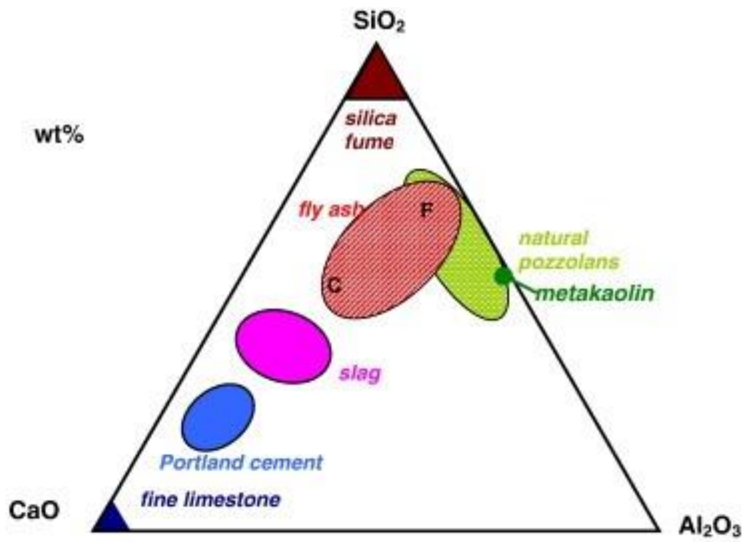


Figure 10: Ternary diagram of cementitious material content [86].

2. The hydrate phases: Figure 11 shows the different hydrate phases that are produced during the hydration process when calcium oxide, silica, and alumina are present. These phases are crucial in determining the properties of the resulting cementitious material.

3. The C–S–H phase and its variations: The extensive range of compositions of the calcium silicate hydrate (C–S–H) phase, which is the most important phase in cement chemistry and that as discussed previously influences the strength and durability of the hydrated cement matrix can be seen in Figure 11.

   The figure indicates that the composition and structure of the C–S–H phase vary depending on the ratios of CaO to SiO2. Other hydration products are also shown.

4. Alumina vertex: Figure 11 shows how aluminum from SCMs can be incorporated into the C–S–H phase, forming C–A–S–H. The presence of aluminum can alter the structure, just like with the PC hydration of tricalcium aluminate.

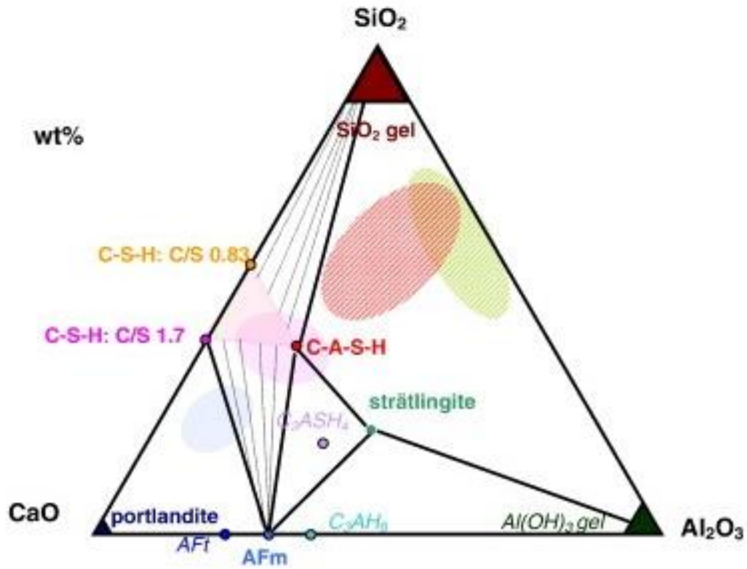


Figure 11: Hydrate phases produced in the SCM CaO-Al_2O_3-SiO_2 system [86]

Some widely used SCMs will be shortly described in this section since in one way or another some of their properties and characteristics can partially be connected to the secondary waste materials studied during project CO2REDRES, especially calcined clays such as Metakaolin due to their origin from natural pure clay deposits.

2.1.3.1 Fly ash

Fly ash is a by-product generated from coal combustion in electric power plants. It bears a strong resemblance to cement in both particle shape and color. During the coal burning process, mineral impurities present in the coal, such as clay, quartz, shale, and feldspar, are subjected to high temperatures. These impurities fuse in suspension and subsequently solidify into spherical particles when cooled, forming fly ash. [113]

The characteristics of fly ash such as morphology and composition are influenced by the combustion temperature and cooling and the mineral composition of the raw coal. Generally, fly ash particles are finer than those of OPC, with sizes ranging from 10 to 100 μm and a spherical shape that relates to the ball-bearing mechanism explained in section 2.1.2.5. Many studies define the fineness of fly ash in terms of surface area, typically between 300 and 500 m^2/kg. The chemical composition of fly ash is primarily determined by the composition of the coal from which it is derived. However, it consistently contains significant amounts of silica (SiO_2), alumina (Al_2O_3), calcium (CaO), and iron (Fe_2O_3) making it an excellent pozzolan. [113], [114], [115]

The pozzolanic activity of fly ash, which is crucial for producing cementitious compounds that contribute to the strength and durability of concrete, depends on several factors. These include the fineness of the fly ash, its calcium content, the structure of the particles, and their size distribution. When fly ash is used in concrete mixtures, it improves the mixture's properties by reducing bleeding and segregation. This improvement is due to the lubricating effect of the spherical ash particles and the increased solid-to-liquid ratio in the mixture.[114], [116]

The use of fly ash in concrete mixtures offers multiple benefits. Not only does it enhance concrete properties such as durability, but it also provides significant environmental advantages being a by-product SCM. By incorporating fly ash into concrete, the need for landfill disposal of coal combustion products is reduced, and natural resources that would otherwise be consumed in concrete production are conserved.

Further benefits of incorporating fly ash into concrete include enhanced workability with a reduced water-to-cement ratio, a reduction in the heat of hydration due to a slower pozzolanic reaction, higher (but gradual) ultimate strength resulting from the additional binder, and decreased permeability due to the lower water-cement ratio and extra cementitious compounds. In hardened concrete, the addition of fly ash significantly enhances resistance to sulfate attacks, corrosion, and alkali-silica reaction (ASR) detrimental to concrete health. These improvements are helpful for the longevity and durability of concrete structures.[20], [114], [116]

2.1.3.2 Silica fume

Silica fume is a very fine non-crystalline material produced in smelting furnaces at temperatures of around 2000°C from carbon as a raw material. It is a by-product of production of silicon metal and its alloys and can exhibit both pozzolanic and cementitious properties. The greyish white silica fume particles are extremely fine with more than 95% less than 1μm diameter, a surface area of about 13,000 to 30,000 m^2/kg, and a bulk density of around 130 to 430 kg/m^3. Silica fume has a high content of amorphous silica, in general more than 90% with very minimal quantities of other oxides. [110], [117] The role of silica fume in concrete can be understood through three key mechanisms that derive from the fact that it is a great pozzolan due to its fineness and chemical composition [117]:

(1) Pore-Size Refinement and Matrix Densification:

Silica fume significantly reduces the volume of large pores in OPC concrete mixes. Acting as a fine filler, it fits into spaces between grains and this densification improves the overall matrix. Please see filler effect.

(2) Reaction with Free-Lime:

This enhances the concrete's strength and durability and happens with the pozzolanic reaction where silica fume consumes carbon hydroxide and forms strength-contributing cementitious hydrates.

(3) Cement Paste–Aggregate Interfacial Refinement:

The transition zone (ITZ) between aggregate particles and cement paste is crucial for the cement-aggregate bond in concrete as seen in section 2.1.2.5. Silica fume reduces the thickness of this transition phase and decreases the orientation of calcium hydroxide crystals, compared to mortar containing only OPC. This results in improved mechanical properties and durability due to enhanced interfacial or bond strength.

The use of silica also improves also other properties of concrete by allowing a very low permeability to chloride and water intrusion, also a superior resistance to chloride and acid attacks as well as ASR. It also enhances concrete structures with an increased resistance against abrasion and impact. Compressive strength of concretes containing silica fume reaches up to 140 MPa, with a high modulus of elasticity exceeding 40,000 MPa, and flexural strengths up to 14 MPa.[117]

Commercially, silica fume is added to cement still in the production plant as a mineral admixture. Among the many applications, such as mortars, grout, and shotcrete, silica fume is used in high performance concrete for bridges, highways, marine, and other structures.

2.1.3.3 Ground granulated blast furnace slag

Ground granulated blast furnace slag (GGBS) is a by-product of the iron industry blast furnaces and is a glassy material having a beige to dark off-white colour, a surface area of around 510 to 685 m^2/kg and a bulk density of around 1200 kg/m^3 its particles range in diameter from 9 to 13 μm. The chemical composition of slag consists mainly of silicates and aluminosilicates originating from the iron ore and some oxides from the limestone: SiO_2, Al_2O_3, CaO, MgO. Slag is made up of both glassy and crystalline phases. The glassy nature (85% to 90%) is responsible for its cementitious properties and is obtained by the quick cooling down of the slag, a process that prevents the formation of large crystals. The resulting material is composed of about 95% non-crystalline calcium-aluminosilicates. Subsequently, the slag is dried out and grinded to a very fine powder known as the ground granulated blast furnace slag. [110], [118]

In cement mixtures, GGBS can be used as a direct replacement for ordinary cement on one-to-one basis by weight. Replacement rates for GGBS vary but usually range between 20 up to 85% depending on the application.

Similarly to other SCMs, some of the most common advantages of using GGBS in concrete are:

- Improved workability of the cement paste by delaying the setting time.
- Enhancement of OPC strength (with partial substitution)
- High resistance to sulfate attacks and ASR.
- Reduction of the heat of hydration.
- Reduced permeability and improved surface finishing.

2.1.3.4 Calcined clays

The reviews and studies published by various authors around calcined clays and their use as SCMs range from topics related to the optimal calcination temperatures, to the cement blend proportions, influences of clay additions on the properties of mortar and concrete, properties of calcined clays, fresh paste workability, addition of superplasticizers, mechanical strength, and long term and durability issues [119], [120], [121], [122]. This section focuses on calcined clays as SCM, starting with an introduction to the structure of clays and their activation techniques, and then exploring some of the properties of metakaolin which is the most used form in blended cements.

2.1.3.4.1 Clay minerals

Clay minerals are a varied group of hydrous layer aluminosilicates that make up a significant portion of the phyllosilicate family of minerals often having particle sizes smaller than 2 μm [123]. Clay particles consist of alternating layers of tetrahedral and octahedral sheets (see Figure 13). The tetrahedral sheets contain silicon cations (Si^{4+}) surrounded by four oxygen ions, forming a pseudo-hexagonal network. The octahedral sheets have aluminum cations (Al^{3+}) coordinated with oxygen or hydroxyl groups (OH^{-}). The tetrahedral sheets connect to the octahedral sheets by sharing the oxygen atoms. The arrangement of these sheets determines the type of clay mineral [102]. There are two main groups:

1:1 Clays (TO): These have one tetrahedral sheet combined with one octahedral sheet, such as kaolinite. See Figure 12.

2:1 Clays (TOT): These have one octahedral sheet sandwiched between two tetrahedral sheets, including illite and smectite. This is the largest group of clay minerals.

The division of clay minerals into the two groups results from the layer arrangement they present and does not cover the rich diversity of all possible variations since clays can also contain complex minerals in which these layers can coexist [119] .

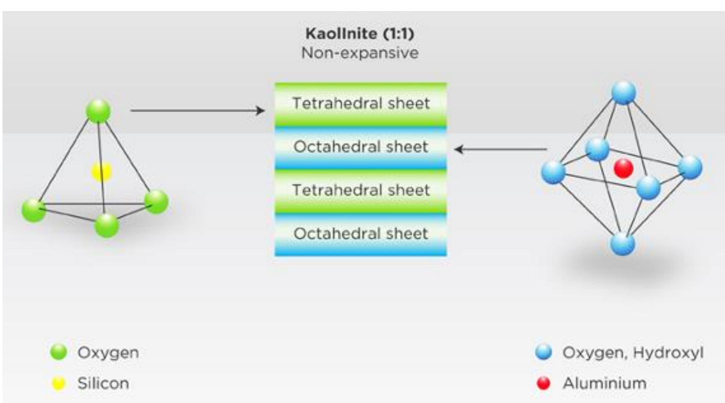


Figure 12. The TO structure of Kaolinite mineral.[124]

2.1.3.4.2 Activation of clay minerals

The pozzolanic activity of untreated raw clays is not usually considered satisfactory [102], and for whatever fineness and particle size distribution, raw clays such as kaolin exhibits little to no chemical reactivity when mixed with OPC [125]. This fact is rather related to the stable crystal structure of clays and their morphology that impedes the filler effect together with their high specific area that leads to the need of a high water to binder ratio [126].

To enhance the pozzolanic properties of clay, its original crystalline structure needs to be modified into an amorphous phase through activation. This can be done mechanically with a process such as milling and grinding to reduce particle size, chemically through adding alkali-rich solutions to improve the solubility of silica and alumina, or thermally through calcination. Table 6 summarizes the activation methods, their action mechanism on the structure of the clay and their limitations according to different authors.

Table 6. Common activation methods and their mechanisms (adapted) [80], [127], [128].

Activation method	Action mechanism	Limit
Chemical activation	Destroy the Si–O bond and reduce the degree of polymerization of the Si–O–Si network structure; provide additional nucleation sites for hydration products and improve solubility of silica and alumina.	May cause the chemical composition of the material to change
Thermal activation	Change the crystal phase into an amorphous less ordered phase and change the chemical structure of materials	High energy consumption; optimal temperature and recrystallization of minerals
Mechanical activation	Reduce particle size and provoke delamination leading to a more open structure, transform crystal structure, and generate lattice defects and deformation causing amorphization.	Grinding time needs control if long enough

2.1.3.4.2.1 Thermal activation

One of the effective methods to activate clay minerals is through thermal activation, also called calcination [102]. Calcination is the process of heating the clay to a target temperature that provokes its dehydroxilation, the point at which the structurally bound water i.e. the hydroxyl group (OH) connected to the octahedral and tetrahedral sheets is released which causes the buckling and distortion of the polymeric structure of the aluminosilicate layers resulting in a collapsed disordered structure [129]. The removal of OH changes the structure of the clay from a crystalline to an amorphous metastable state makes silicon and aluminum more reactive with calcium in lime or cement, aiding the formation of new cementitious phases desirable for the pozzolanic effect [102]. Additionally, calcination improves the workability of the clay-cement paste by reducing its water demand compared to untreated clay [130]. Figure 13 shows the natural pre-calcined layered structure of kaolinite clay seen under a microscope as compared to the amorphous transformed morphology of calcined kaolinite, also known as metakaolin in Figure 14.

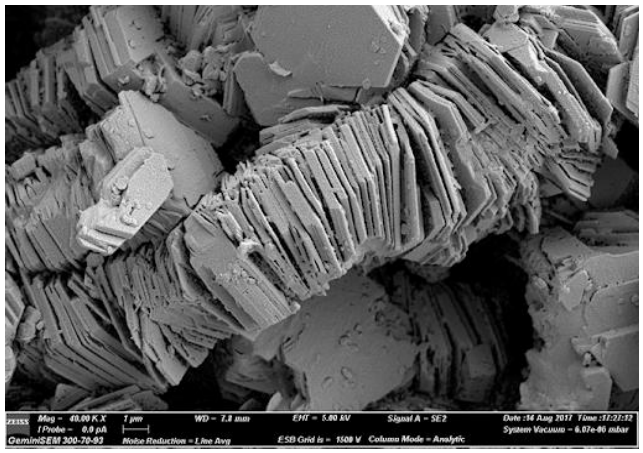


Figure 13. Morphology in form of plates of clay mineral Kaolin through Scanning Electron Microscopy.[131]

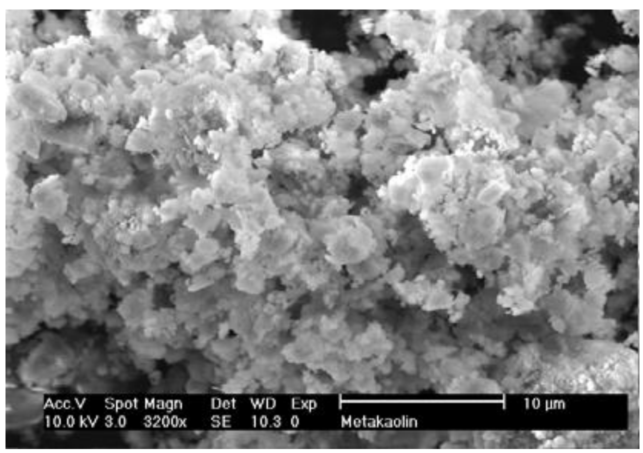


Figure 14. Morphology of metakaolin powder through Scanning Electron Microscopy.[130]

During calcination several stages can be distinguished at different temperatures [92], [102], [110], [119], [120], [126], [132], [133], [134]:

1. 30 to 60°C – Water evaporation happens and there is no influence of the mineral structure of the clay.

2. Around 100°C (sometimes up to 300°C) - The removal of adsorbed water situated in between the T and O layers, this is referred to as dehydration.
3. Between 500 to 850°C – The dehydroxilation temperature is unique for each clay minerals and can be affected by factors beyond the bonding of hydroxyl groups to the TO layers, such as crystallinity and particle size distribution. It varies also significantly for mixed clays depending on their major content. Kaolinite usually achieves its full dehydroxilation at an optimal temperature of around 600 to 750°C, and illite at a slightly higher upper range reaching 800 to 900°C.
4. Greater than 850°C/900°C – In this range sintering and recrystallization can happen with the formation of non-reactive/inactive high-temperature phases. Sintering is the phenomenon observed when the clay particles agglomerate as the result of the amorphization they undergo at high temperatures, whereby the clay structure is altered and densified. For kaolinite the crystalline phase mullite can already form at 950°C and for illite at 850°C. Illite is considered the trickiest since the optimal temperature that causes its amorphization is almost the same as the one that causes partial recrystallization taking place at the same time and thus reducing its pozzolanic potential according to some studies.

The focus on illite and kaolinite and not other clay types throughout this section is related to the fact that they are the most abundant in the samples studied for project CO2REDRES.

The calcination permanence time at the target temperature is also an aspect that has been researched and reported. According to [119], in 23 experiments performed, calcination times ranged from 1.32 to 4.68 hours, typically around 3 hours. Longer calcination times improved mortar strength when the temperature was below 700°C but had a negative effect above this temperature. Other factors such as the calcination method, the material fragmentation, pre-treatment, and device type also influence the process. It is important to note that these remarks do not apply to flash-calcination, a distinct method, that lasts only fractions of a second to several seconds.

2.1.3.4.2.2 Mechanical activation

Mechanical activation of clay involves the use of a mechanical process such as grinding and milling. It can be done separately or in combination with the other two activation methods, the chemical and the thermal, and it has the same objective of changing clay's physical and chemical structure to a more reactive phase [119]. Research articles studying mechanical treatment have shown that this technique is able to achieve partial dehydroxilation [135] and amorphization [134], [136] of clay minerals.

Since the effectiveness of the thermal process depends on many aspects and one of them is the particle size, some authors indicate that clays should be grinded before calcination [119], [137]. Mechanical activation is also desirable after calcination to combat the coarsening of clay particles because of agglomeration and/or sintering, since agglomeration of the clays can already start at low temperatures where the particles stick together although not changing their structure just yet, all the way to the sintering phenomenon happening with amorphization. This results in the decrease of the clay's specific surface area which requires fixing through mechanical grinding.[102], [135], [138]

The effect of mechanical activation on the pozzolanic activity of clay materials is generally related to the smaller the particle size which then conveys stronger pozzolanic activity [80], and in some cases when grinded for a longer period (10 hours or more) with high energy the loss of hydroxyls through dehydroxylation [135]. This happens because the mechanical energy from grinding is converted into the surface activation energy of the material during the process, which helps increase its lattice defects and superficial active sites, therefore enhancing its activity.

Generally, researchers often point that the synergistic treatment of compound activation methods is more conducive to the improvement of the clay's pozzolanic activity, such as thermal and mechanical activation that are common combinations.

2.1.3.4.2.3 Chemical activation

Just like the previous activation methods, one of the objectives of chemical treatment of clay minerals is the amorphization of its structure through partial dissolution and can include alkali or acid treatments [134]. The focus of this thesis is oriented towards mechanical and thermal treatment methods. More on this topic is discussed under subsection *Alkali-activated binders*, which delves further into the concept of using chemical activation to create hardened binders and geopolymers with clay based material rich in alumionsilicates, and is more relatable to project CO2REDRES and the types of materials investigated during the experimental research.

2.1.3.4.3 Metakaolin

As presented previously in this section, Metakaolin (MK) is a calcined clay obtained from kaolinitic clay one of the most used clays commercially [139]. MK is considered a pozzolanic material and its calcination process happens between 500°C and 800°C [120]. The raw material, kaolin clay, is a fine, white mineral traditionally used in porcelain production. During calcination, kaolinite (hydrated aluminum disilicate) undergoes dehydroxylation, losing its water content and transforming into metakaolin, which retains a disordered, amorphous structure that is highly pozzolanic.

As it is the case for other calcined clays mentioned previously, the effectiveness of MK as an SCM depends on achieving near complete dehydroxylation without overheating, which would cause sintering and lead to the formation of the non-reactive phase mullite in the case of kaolinite. From the pozzolanicity perspective, MK reacts with calcium hydroxide at ambient temperature to form calcium silicate hydrates and other alumina-containing phases, that would then fill the micropores reducing porosity and improving the concrete strength, enhancing its pozzolanic properties just like other pozzolanic materials.

Since the secondary raw materials studied in project CO2REDRES have major clay phases, the literature on MK is important to establish parallels in the study with a material that has been widely investigated, despite the heterogeneity of the materials studied, that are based on the industrial process of gravel wash and decantation, and the geographic location of the quarries.

2.1.3.4.3.1 Properties of Metakaolin

The chemical constitution of MK might slightly vary from one source to another but is mainly SiO_2 (more than 50%) and Al_2O_3. Other compounds such as ferric oxide Fe_2O_3 and calcium oxide CaO are also found in MK. Physically MK has extremely small particles when compared to other SCMs with an average size of 3 µm, and it naturally exists in the form of an off-white powder [120].

The reactivity of MK is dependent on its chemical and physical properties and are generally set by standards such as NF P18-513 [140] and ASTM C-618 [105].

Desirable chemical properties include amorphousness and oxide composition since reactivity in MK is linked to its non-crystalline, amorphous nature, and elevated levels of reactive SiO_2 and Al_2O_3. On the physical properties side, fineness, and Particle Size Distribution both play a significant role where typically, greater fineness and a finer PSD improve MK's reactivity [125]. With an increase in fineness, the direct chemical reaction between MK and lime is facilitated. This parameter is important to understand how the grinding of calcined clays influences the reactions in the cement-MK matrix, that will reflect on the methods later on chosen for the experimental part of project CO2REDRES.

Among the studies cited by Siline and Mehsas [125] investigating the effect of fineness of MK on its reactivity, there is Mitrović and Zdujić's [141] that showed that longer grinding times lead to finer particles, reduced particle size distribution (PSD), and improved reactivity of the studied MK sample. Vicayno et. al [142] investigated the effect of mechanical treatment on compressive strength and concluded that the strength of 20% MK mortars at 28 days increased with the increase in grinding time, therefore correlating higher specific area with better performance. Similarly, Ouyang et al. [143] reported that the decrease in particle size with increased milling time after kaolin calcination at 700°C for 2 hours increased the MK reactivity. All these studies as well as other similar ones confirm the need for reaching the finest possible calcined clay as means of optimizing the chemical reactivity as long as the fineness of the clay does not increase the water demand required for workability drastically.

2.1.3.4.4 Effects on the addition of calcined clays to cement systems

Calcined clay additions to ordinary Portland cement (OPC) impact both fresh and hardened concrete properties, similar to other pozzolanic materials, and in this section the focus will be on MK, as the most used and studied of calcined clays. Studies on the porosity and pore size distribution in cement pastes with MK have shown that MK additions help reduce porosity up to a substitution level of 20-30%. However, above 30% substitution, porosity increases due to the decreased effectiveness of the pozzolanic reaction, leaving some MK unreacted and too coarse to fill micropores, which reduces compressive strength. Another aspect of porosity in the cement-MK matrix is that unlike in ordinary cement concretes, porosity in concretes containing MK is not proportional to the water/cement ratio. When used as an SCM, the ideal substitution percentage of OPC by MK depends on its purity that defines its reactivity, a parameter which affects the hydration reaction and hence its products.[18]

In dedicated publications on Metakaolin use as an SCM, various authors, Siddique and Khan [120], Wang et. al [144] and Khatib et. al [65] describe some of the advantages of the use of MK that were studied and reported throughout the literature. According to the cited authors, the addition of MK can cause an increase in compressive, tensile, and flexural strength of concrete up to a certain level of substitution, compression strength being the most studied parameter. Concerning durability parameters, the MK in the matrix assists in reducing the permeability of the hardened concrete and consequently allowing higher resistance to chemical attack and the reduction of harmful alkali-silica reaction. The overall extension of the lifetime of a concrete structure with MK, helps as well in decreasing maintenance requirements. Regarding long term effects, a reduction in shrinkage is usually observed, and certain studies reported by those authors show that a replacement of OPC with 20% MK can reduce the long-term shrinkage by more than half. Naturally, those advantages are application oriented and depend on the rate of substitution of OPC by MK as well as the quality of MK used.

The fresh properties of cement pastes and mortars are not the subject of this thesis; however, it is important to note that the addition of other materials to cement can affect its workability due to changes in the standard consistency and setting time provoked by these additions. In the case of calcined clays, researchers have observed an increase in water demand in some cases and it could be attributed to the particle size distribution and the high fineness and in the case of metakaolin, also affecting the setting time metakaolin cement pastes. In one study [145], a substitution rate of up to 10% presented similar values for water demand and setting time as in the reference sample, whereas at 20% a delay of the setting tie started to be observed.

2.1.3.4.5 Other concepts with calcined clays

As the previous parts of this section established, the literature on the use and activation of clay minerals and their applications in concrete and mortars is extensive and covers an array of issues. This literature review focuses primarily on the use of calcined clays as supplementary cementitious materials (SCMs) in binders, where cement is the primary component, and in cement-based concrete. However, it is important to highlight that there are other concepts that are based on the use of calcined clays, such as cement-free binders, which form the basis of geopolymers, as well as other alkaline-activated binders, including or not those involving clay minerals. These excluded topics will be shortly touched upon here, though not fully detailed due to their distance from the developed research methodology.

2.1.3.4.5.1 Alkali-activated binders

Alkali-activated binders are primarily synthesized by activating calcium-rich materials like blast furnace slag with alkaline solutions, resulting in durable binders with high compressive strengths [146].

The development of alkali-activated binder (AAB) technologies has evolved substantially over the past century, beginning with foundational research in the early 1900s and advancing to recent large-scale applications worldwide. The origins of AAB date back to 1908, when Kuhl developed AAB using alkalis (NaOH and KOH) with ground slag, earning the first patent in AAB technology. Since the 1980s, AABs have gained acceptance for infrastructure, including rigid pavements, structural members, and precast applications[147].

The alkali activation mechanism (Figure 15) involves dissolving aluminosilicate materials in an alkaline solution, forming reactive Si-O-Si and Al-O-Si bonds that develop into a hardened, polymeric network, where two types of mechanisms can be distinguished [146], [147], [148]:

1. Calcium-rich systems (like blast furnace slag): Moderate alkaline activation leads to C-S-H phases just like in cement hydration and is responsible for high strength.
2. Low-calcium systems (e.g., fly ash or metakaolin): High alkalinity results in N-A-S-H gels, which also have high strength. The Si+Al system, activated by stronger alkalis, aligns with “geopolymers” due to its polymeric, zeolite-like structure.

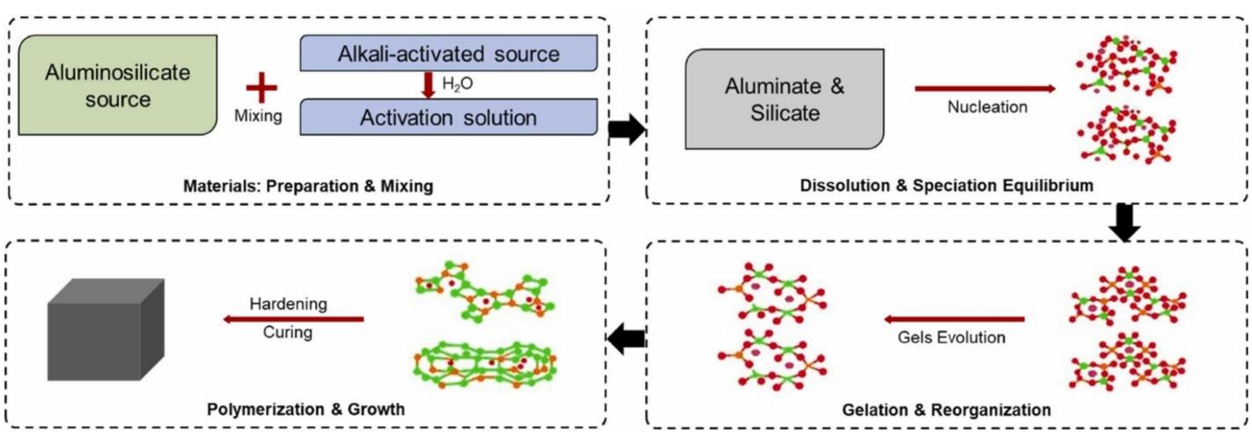


Figure 15. Simplified conceptual model of alkali activated binders formation [147].

Studies on AAB related to calcined clays and specifically GWM show that the material is a promising precursor (the raw material that undergoes activation) for geopolymer synthesis. In a study by Wagner [149] , GWM was thermally activated at 850°C then chemically activated using NaOH and KOH, the results showed that samples reached maximum strength after 56 days of curing, particularly those activated with KOH and that the separation of fine particles (<20µm) from the bulk GWM, allowing the removal of quartz and concentrated clay, increased compressive strength 3 times, showcasing the potential of calcined clay in AAB applications.

However, the success of AAB applications depends on many factors which highlights the remaining challenges to overcome such as variability of clays and treatment needs, reactivity and composition (Si:Al ratio), and processing challenges [134]. A study on GWM and silicate dust from Germany showcased the possibility of producing alkali-activated cement with zero carbon emissions in a cost-effective way activated with an NaOH solution after thermal and mechanical treatment [150]. On the other hand, Luxembourgish origin GWM containing kaolinite and illite studied as a potential precursor for AAB at different temperatures achieved relatively low compressive strengths despite the promising mineralogical and chemical composition highlighting the possibility of needing extra additives or admixtures in the system to make it feasible [71].

2.1.3.4.5.2 *(Low carbon) Lime Calcined Clay Cement - LC^3*

In line with the emission reduction agenda, LC3 is a concept that aims to reduce drastically the quantity of clinker content in concrete going below 50% in some cases [151]. This approach leverages the synergistic effects between two SCMs: calcined (mostly kaolinitic) clay and limestone. The combination of the aluminates from the calcined clay and the carbonates from limestone enhances the pozzolanic reaction in the system and consequently reduces considerably the need for clinker. Since clinker production is the most CO_2-intensive step in cement manufacturing (see section 2.1.2.1), reducing the clinker content has a directly proportional effect in the CO_2 footprint of cement production. Additionally, because the limestone ($CaCO_3$) in the mix isn't calcined, no extra CO_2 emissions are generated from its inclusion, which further enhances the low-carbon nature of the cement.

According to the LC3 portal [152], the cement known as LC3 is recognized for its environmentally friendly production process, which emits less CO_2 compared to traditional OPC. LC^3 typically contains 50% ground Portland clinker, 30% ground calcined clay, 15% ground limestone, and 5% ground gypsum, often referred to as LC3-50. This blend can achieve mechanical properties similar to OPC within seven days if the clay has at least 40% kaolin. Other studies that reported on mechanical performance showed mixed findings depending on specific formulations and conditions [153]. LC3 mortars typically show slightly lower compressive strength than traditional OPC mortars, yet they remain suitable for many applications, even with different replacement levels. In some cases, a reduction in strength has been observed, primarily due to slower hydration and phase development, which may limit LC3's application in high-strength requirements. The impact of increased LC3 binder ratios is also notable, as higher replacements can reduce compressive strength due to a dilution effect that limits calcium hydroxide availability for pozzolanic reactions. However, certain concrete grades using LC3 have demonstrated comparable strength growth over time to OPC, especially in structural applications where long-term strength development is critical. Overall, these findings suggest that while LC3 may offer slightly lower compressive strength than OPC, adjustments in binder ratios, curing practices, and clay content can make it a viable option for sustainable concrete applications.

Other studies on economic and environmental potential mostly agree on the related advantages of using LC3 as a sustainable alternative to OPC in reducing greenhouse gas emissions and improving efficiency. In Cuba, a study emphasizes the robustness of LC3’s environmental benefits despite potential changes in fuel types, though economic benefits are sensitive to transport distances and the availability of secondary fuels [154]. Similarly, a Brazilian study underscores LC3’s environmental advantage over OPC, noting especially low impacts when waste materials are used, which reduces extraction-related emissions [155]. The two studies recognize challenges in transportation and material sourcing; however, the Brazilian study finds transport feasible over longer distances and points to variations in environmental performance based on clay purity.

Overall, the different researchers point to further research necessity into long-term performance and durability of LC3 as a main point for advancing the use and spread of this material technology.

2.1.3.4.6 Gravel Wash Mud

Gravel Wash Mud (GWM) as the name suggests is a byproduct of the industrial process of washing gravel to remove impurities such as clays, silts and other fine particles adhered to the stones before it can be used in the construction industry. The washing process produces a mud like slurry containing such sediments and minerals that were washed off the gravel and is usually deposited in basins that can pose disposal challenges, mostly of environmental nature.

A series of research studies performed on GWM [24], [25], [27], [71], [146] have shown its suitability for use as an SCM, particularly as a partial OPC substitution in binders. Its addition as a calcined clay rich in aluminosilicates has a confirmed pozzolanic potential, enhancing compressive strength when used as a filler material in cement mixtures. While the findings are promising, the conclusions point to the need of additional research to scale up raw material processing, optimize mix proportions, and investigate the rheology, durability, and other properties of both fresh and hardened concrete containing calcined GWM. These steps are considered by the authors essential to develop a sustainable, low-carbon concrete product for construction applications.

One of the interesting aspects about GWM is its differences with regards to mineralogical composition when compared to pure clays that are already known and used as SCM on the market. The wash slurry is obviously not made up of pure grade clay, and in this context research on impure clays can also be considered as input for comparison. In a study on low-grade clay with 14.6% kaolinite being used as SCM [127], the kaolinite content transformed from crystalline phase to amorphous metakaolin phase at 600 °C and showed increased pozzolanic activity between 700 and 800 °C leading to a conclusion that supports a substitution rate of 10–20 wt% of OPC.

In general, the literature on clays used as SCM is complementary to that on GWM since the main phase researched for potential pozzolanicity in the latter is the clay content. In a study on clay suitability [156], the authors suggest a methodology to assess the suitability of clays from a particular deposit by looking at their chemical composition, loss on ignition after calcination, and amount of kaolinite. More specifically the alumina (Al_2O_3) content, which should be more than 18%, and the ratio of alumina to silica which should be greater than 0.3 according to them. Regarding the kaolinite content, there are multiple studies in the literature on the optimal percentage, although certain studies have demonstrated that even clays with low purity (defined as those that have more than one type of clay and a significant quartz content) can be considered suitable for use as SCM depending on the circumstances.

The research gap on GWM is therefore characterized by the lack of a common framework that can fit and describe the properties of this group of materials, and this is due to two factors. Firstly, the heterogeneity of those materials that can be blends of different layers of clay and present varying degrees of pozzolanicity when applied as SCM. Secondly, the fact that as recently studied materials that have not been intensively investigated (as opposed to pure clays or other industrial by products used as SCM), makes the characterization of new materials and deposits important to know better if these materials tend to present similar properties when used as SCMs as a function of their chemical and mineralogical composition. Therefore this research, will help fill in this gap by studying multiple materials from the Greater Region that can fit this use and create a better understanding of the potential and similarity of those different GWMs.

2.2 Review of relevant literature CO2REDSAP

The circular economy (CE) has emerged as a prominent framework aimed at rethinking the traditional linear models of production, consumption, and business, grounded in principles of resource efficiency, waste minimization and elimination (depending on the school of thought), and the continuity of loops in material use. As this concept gains traction, it is increasingly seen not just as an economic model but as a transformative pathway towards a more sustainable future. However, while certain defenders of CE promise systemic change, it is not without critique – questions remain about its implementability, scalability, and potential to decouple economic growth from potential harm emphasizing the restoration of natural systems and the cooperation between humans to evolve together with the economy while respecting ecological wellbeing. Within the built environment, the CE is applied across multiple dimensions including material aspects, structures, digitalization, the development of standards and certifications, all promoting sustainable and or circular construction practices. The objective of this chapter is to give a background of all these concepts and synthesize the current literature to explore those interrelated aspects, providing a comprehensive view on the role that CE plays in transitioning the built environment. At the end of this section, a specific highlight on the policies of the EU that influence CE in the construction sector are presented as a transition and connection to the national policies of Luxembourg that are discussed later in the data analysis and discussion of chapters 6 and 7 respectively.

2.2.1 An introduction to the history of circular economy

When one thinks of circular economy in a holistic perspective beyond promoting closed loop systems and minimizing waste generation while maximizing resource efficiency, a paradigm shift in the way we approach social-ecological-economic systems stands out as a highlight of the process, yet this and other visions are only achievable because of the historical evolution of the circular economy concepts that have been present in several schools of thought from ecological economics to regenerative design and industrial ecology amongst many others.

Long before engineers rethought design, they stumbled upon other basic issues in the industrial landscape. There was a long way from *The Limits to Growth* report for the *club of Rome* in 1972 [157] discussing efficient recycling methods and waste collection techniques to reduce pollution all the way up to the idea of circular society [158] in 2019 as a regenerative concept of an ecosphere, a technosphere and a sociosphere in balance with one another and respecting planetary boundaries. While the earlier messages still hold, science is at a comparatively much-advanced phase of understanding the challenges humanity faces today.

Many authors including [159], [160] distinguish three different periods in the history of circular economy mostly around (i) pre-1990s, (ii) 1990 to early 2000s and (iii) 2010 to the present date. The first period involves the early conceptualization and ideas that laid the foundation for circular economy as we know it today and it coincides with the circularity 1.0 period (Figure 16)

The second period marks the start of the rise of circular economy as an acknowledged concept and the development of key theories, fundamental frameworks, and practical applications [160] In the circularity 2.0 phase, important concepts materialize such as industrial ecology, a subject extensively researched by Robert Ayres since the 1960s [161], who later on argued that there is no limitation to total recycling as secondary recovery is always an option in a stable recycling system [162]. Ayres' vision of an industrial ecosystem is one in which primary consumption of materials and energy is optimized and effluents of the process are raw materials for another. Another important concept is the cradle-to-cradle notion that suggests that humans can learn from nature by establishing a more harmonious partnership with one another and taking it a step further into learning from nature to design processes that contribute biodegradable materials to ecosystems, recycle technical materials, and create self-regulating systems [163].

The third period, which is mostly the one we find ourselves navigating today is circularity 3.0, and although its start varies from one author to another it unquestionably covers the early 2010s onward. It builds on a set of earlier concepts to deliver maximal encompassing views that cover material and energy efficiency, regenerative capitalism, and eco-system economy.

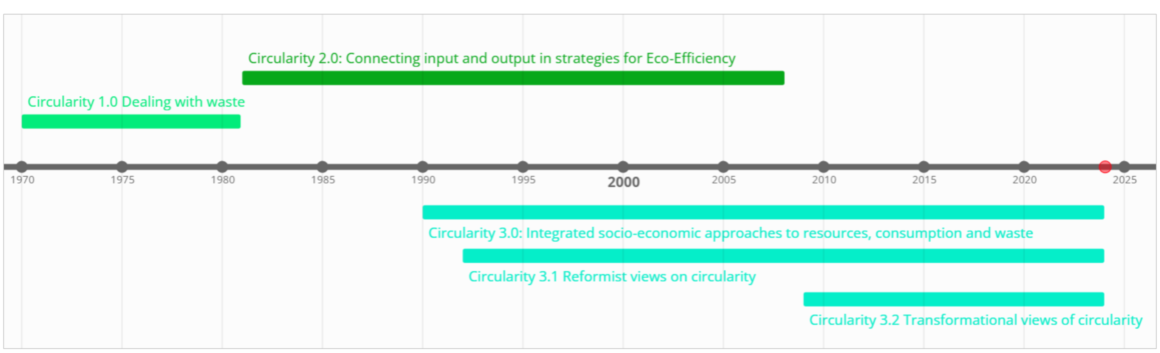


Figure 16. Circularity timeline (inspired by project CRESTING).

Throughout the years, the different interpretations of circular economy varied regarding many aspects such as how holistic, or to what extent are they related to the environment or the economy, how much of the concept is technical and relates to closed loops, if it belongs in the industry or beyond it, etc. Some of those different concepts – designated at schools of thought are presented in Figure 17.

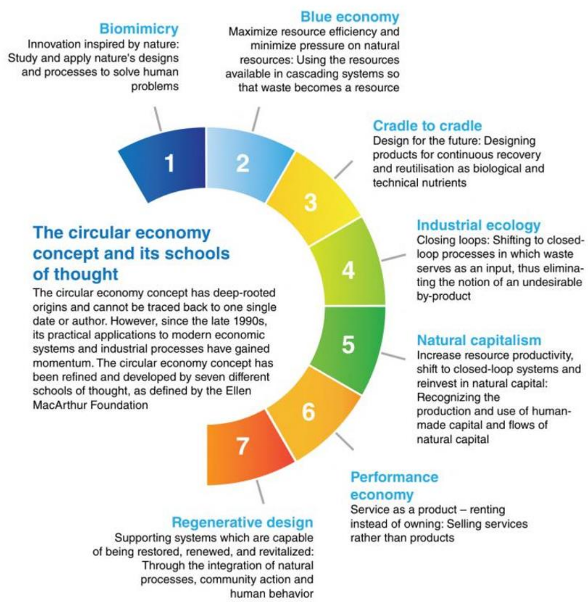


Figure 17. The circular economy in a nutshell – Interreg project MOVECO. [164]

2.2.2 Principles of a circular economy

Omnipresent in most discussions about sustainability, the principles that form circular economy as a concept or a strategy are many. One of the main ideas that define circular economy is the closed loop concept through which the same resources are repeatedly used in a system without the input of further virgin resources. This basic idea is *a priori* common to most authors dealing with the subject, as well as the importance of always keeping materials and material flows at their highest utility and value in a defined system.

According to the British Standard 8001:2017 [165] ,which sets a practical framework for implementing the principles of circular economy, those can be divides into six parts as shown in Figure 18.

Figure 18: The circular economy principles according to BS 8001:2017 [165].

However, the core principles of circular economy can take multiple forms and are driven by design concepts or practical actions on multiple dimensions. In a different approach than the one set by the British Standards Institute, the Ellen Macarthur Foundation [166] distinguishes three design driven principles that are: (1) the elimination of waste and pollution, (2) the circulation of products and materials at their highest value, and (3) regenerating nature. Still according to [166], in rethinking the way companies design their products and consumers make their choices, waste can be stopped before being created and nature and society can thrive.

Starting from holistic views that complement the economic part with nature and society, the term regenerative made its way to circular economy giving a broader perspective on what was once seen as a sustainable business model to substitute the linear economy. The regenerative approach to circularity will be discussed posteriorly in section 2.2.6.5.

However, it is at a further micro level that divergence shows between views presented by different authors. Some defend the idea of a completely closed system while others claim that in its realistic imperfect form, the use of virgin resources is still needed [167].

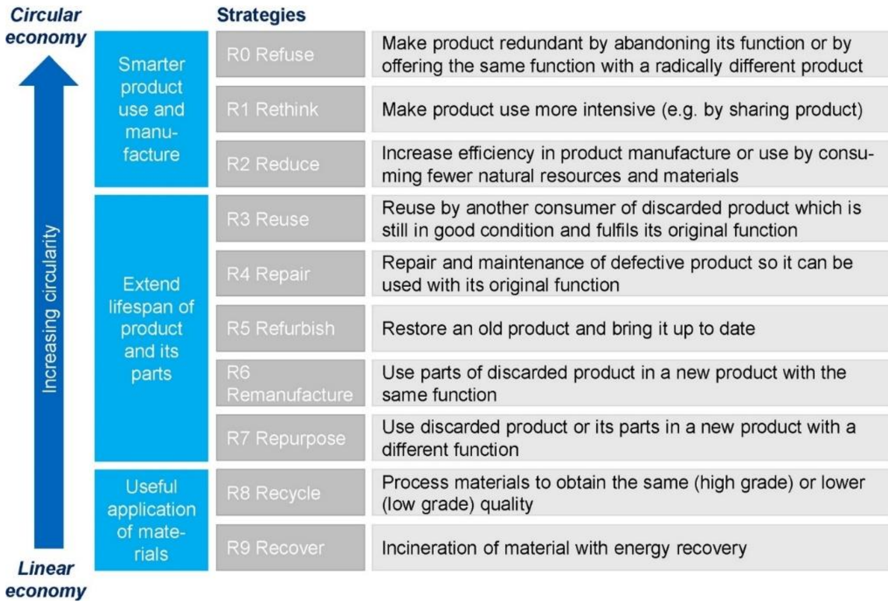


Figure 19. The 9R framework of the core principles of circular economy [168].

The levels of operation of circular economy are also disputed, for example describing at which system level is it more efficient for change to be implemented and therefore to happen, if at micro, meso, or macro level. In a study analyzing 114 definitions of circular economy, only a few definitions mentioned requiring a fundamental change simultaneously at all three levels, whereas most other definitions including a systems perspective focused on the macro-system requiring a complete reform of the ensemble of human activity [168].

Another comparison directed at the aims of the circular economy confirmed that only 12% of the studied definitions explicitly included notions of sustainable development or a holistic view on environment, economy, and society. A three-dimensional sustainability concept taking into consideration environmental aspects, economic prosperity and social equity is important since the lack of one of the dimensions could lead to a lacking implementation, often in social considerations [168].

As one can conclude from the abundant amount of literature present, holistic views on circularity that expand beyond the technocentric solutions are rather new and remain in conceptual development [158], therefore showing a research gap especially in engineering, being a very technical field that often stops short of discussing important key issues that affect circular strategies such as regenerative practices, ecosystem limits, planetary boundaries, and social wellbeing, among others.

2.2.3 The circular economy in practice

As the principles of circular economy can adapt from one source to another depending on the field and the focus of the strategy, in practice it can be condensed in concrete actions that are related to the technical and biological cycles [166].

The technical cycle refers to the stages that help keep materials and products in use for as long as possible, preventing them from becoming waste, whereas the biological cycle focuses on regenerating nature by returning materials safely to the earth. These cycles are illustrated in the Butterfly Diagram (Figure 20).

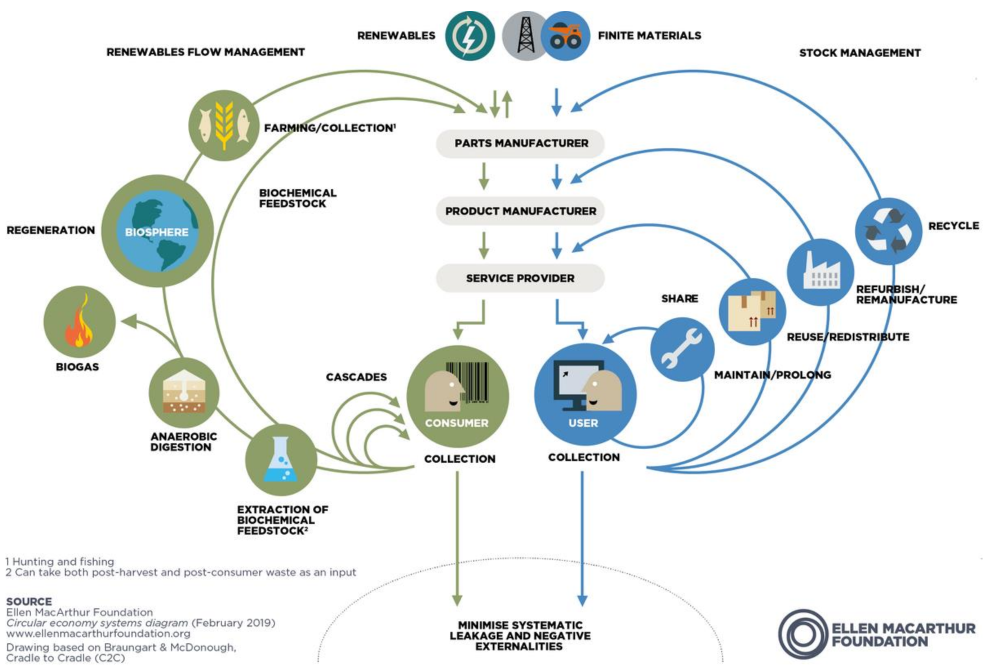


Figure 20. The butterfly diagram describing the biological and technical cycles of circular economy [166].

Just as the 9R framework strategy presented in Figure 19, the technical cycle (in blue right-hand side in Figure 20) embeds the concept of maximizing value by retaining products in use for as long as possible, with recycling being the last resort when further reuse or remanufacturing is no longer viable. The inner loops (such as sharing and maintaining) capture more value, while the outer loops (remanufacturing and recycling) involve more intensive work but still strive to prevent materials from becoming waste.

The biological cycle on the other hand is focused on regenerating nature by safely returning materials to the earth. Through regeneration, natural systems like soil, biodiversity, and ecosystems are actively rebuilt through practices such as regenerative agriculture for example, which enhances soil health, biodiversity, and captures carbon.

Often enough, products have components that belong to both cycles, which makes understanding the mechanisms of each cycle crucial, first for design and then for application of the actions in each cycle at each level for it to be feasible.

2.2.4 Critiques of the circular economy in literature

While acknowledging the positive perception of the circular economy that is often proclaimed as a solution to sustainability challenges, it is not without critics who highlight several concerns and limitations that range from theory to practice.

2.2.4.1 Specific and technical aspects

In a study researching the concept of CE and its limitations [169], the authors defend the idea that circular economy is loosely based on a collection of fragmented ideas from semi-scientific concepts (practitioner developed and oriented), and they redefine circular economy to cover economic, social and environmental objectives, i.e. the three dimensions of sustainable development, to subsequently map six limits that they present as challenge groups to circular economy such as its thermodynamic limits, system boundary limits, limits of governance and management, and limits of social and cultural definitions. In the spatial and temporal system boundary limitations the authors cite that CE projects should "*be considered for their contribution to global net sustainability*" which leans towards a rather different direction of assessing circular actions not based on economic value created by measuring systemic positive outcome. In the last limit group, they discuss the limit to circularity concerning waste definition and how the concept of it is always constructed in a certain cultural, social and temporal context that is dynamic and which has an influence on how the waste issue is handled. Ultimately, the way society defines waste is the way it deals with it.

In another study [170], the authors look at circularity through the lens of a paradigm that integrates various frameworks such as Life Cycle Assessment (LCA) and Cradle-to-Cradle (C2C). However, they argue that not all frameworks are good strategies and most of them focus on palliative actions rather than aiming to decouple economic growth from environmental degradation, because they address the effects (to reduce impact) rather than the causes (to create value). For them, CE should be a bioinspired paradigm that aims beyond recycling materials or identifying their impacts through LCA, and more into bio-design and regenerative actions.

A third study [171] focused on theoretical aspects such as definition and implementability, concluded that the circular future is a work in progress that is not yet mapped out and that there exists a clear need for conceptual coherence about all the aspects of CE to avoid the collapse and obstruction of new knowledge and ways of thinking that might result from divergences. Another important finding was that "*research needs to go out of disciplinary silos*" if society is to achieve a strong circularity culture, otherwise solutions will always stimulate weak circularity based on the business-as-usual notions of no limits and the use of secondary resources and recycling as circular strategies. Other punctual limitations mapped were the inappropriate technologies, economic barriers and capital requirement, rigidity of consumer behavior, and the lack of means to properly measure circularity.

Most critics agree on the disciplinary origins of circularity within science having a very technical orientation that is always vague regarding how it will address the social dimension of the problem it tries to solve, since engineering and natural sciences laid ground for most of the concept of CE [169], [171], [172]. On the research side, [173] goes further into stating the risks that the general lack of consideration of socio-political aspects in CE can generate such as taking up assumptions that CE can be a technological fix for making the current economic system entirely sustainable without questioning persisting negative externalities and existing consumption patterns for example.

Another critical discussion on top of the social dimension is on the unclear contributions to environmental sustainability as well since the boundaries are often blurred between sustainability and circularity despite the former being more holistic [171]. Naturally, not all circular solutions are sustainable, and the focus on incremental improvements to CE, although well intentioned can sometimes do more harm than good [174], just like in the example of recycling of glass bottles into insulation material assessed by means of LCA, being an option that offers better environmental performance than a closed loop circular strategy of recycling the glass back into the original bottle form [175]. This is a specific example, that might illustrate where tightly closed loop circularity fails on one count i.e., environmental category, but still shows that the solution is certainly not a linear concept, but rather an alternative circular approach. Therefore, the question also needs to be whether LCA is an all-encompassing tool or not, and which are the tools that we use to assess circularity and what do these conceal and reveal.

2.2.4.2 System aspects

On the broader side, some authors question the relation of circularity to sustainability with a system view perspective considering holistic aspects and not just one of the sustainability pillars as discussed previously.

For *Bosschaert* [176], the practical and valuable tools of circularity developed for specific functionalities often overlook system dynamics, which encompass critical issues such as the rebound effect, the tragedy of the commons, and law of diminishing marginal returns. To avoid exacerbating existing problems, it is essential to integrate the study and analysis of these systemic dynamics into CE projects.

With the definitional quagmire [171] discussed previously, some authors [169], [177], [178] describe the circular economy as characterized by conceptual fragmentation and lack of paradigmatic strength according to those, and this affects the practice at a systemic level where the fragmented technocratic view of circularity is unable to address ontological and epistemological questions faced by society [179].

According to [179], for CE to succeed in solving the problems it desires to solve, it requires a close examination of the foundation of our economic systems where it is embedded. A circular economy that is tied to the premise of unlimited growth and aligned with the mechanistic worldview of mainstream economics where actors are isolated individuals of no collective value, and nature is merely an economic tool will clearly not achieve any solution to the posed challenges. On the other hand, a CE that has ecology at its heart and views economy at the service of nature and society through the lens of an organic worldview, while embedding regenerative practices to find innovative solutions without being constrained by the need for unlimited growth has better chances at being a concept that works.

In summary, limitations and shortcomings of CE can be classified into two categories. The first (1) related to spatial temporal factors that are related to universal realities that cannot be changed, such as laws of thermodynamics and the finitude of resources. The second set (2) however, is very human dependent and is associated to the overall ruling economic system, and the worldviews that influence individuals, organizations, and society in general.

2.2.5 Circular economy and transitions

When circular economy collides with sustainability and connects to the future of society, the idea of a transition space from the status quo to a new reality is established, and this is not a specific aspect for one sector or another as the transition happens on various scales. The notion of "transition" as described by [180] emphasizes a long-term process of change, representing a transformation that is considered profound and fundamental that focus on the development and implementation of innovations that lead to major shifts in current systems. In one of the most used definitions by *Loorbach et al.*, the concept of transitions refers to fundamental, systemic changes in complex societal systems, shifting from one stable state to another through nonlinear, often disruptive processes. These shifts result from interactions between different levels—macro (landscape), meso (regimes), and micro (niches)—which influence and reinforce each other.

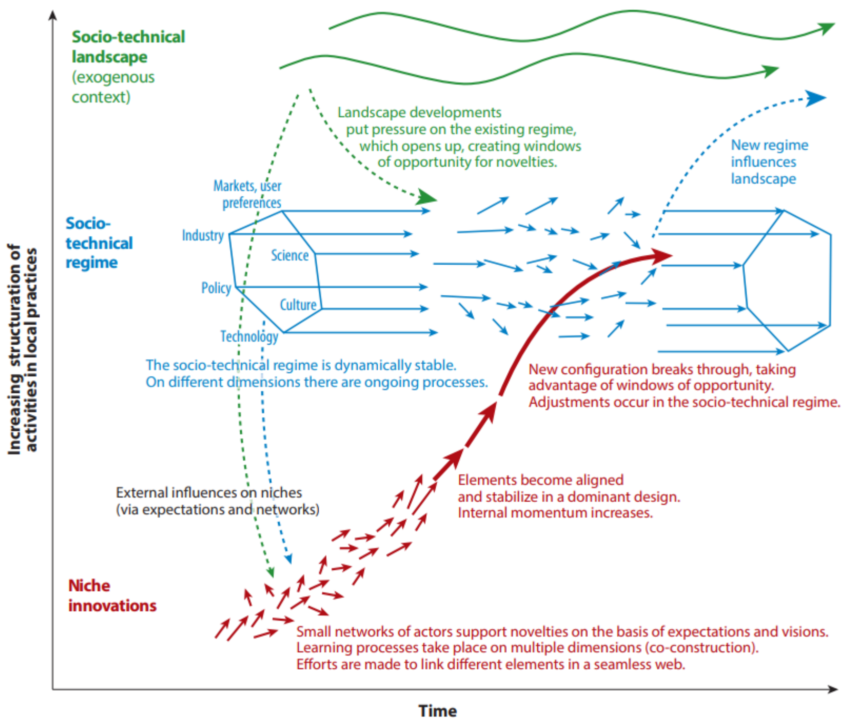


Figure 21. The multilevel and multiphase transition concept by Loorbach et al. [181]

Transitions research explores how societies can shift from unsustainable systems toward more sustainable ones by understanding and influencing these disruptive transformation processes [181]. In the built environment, the transition aspect has been studied over a range of topics in urban and rural settings alike, involving natural resources, building performance, materials, neighborhoods, etc. Transition studies typically explore successful ways and strategies towards an envisioned sustainable future. One example of such initiatives is the *Luxembourg in Transition* consultation [182], that gathered multi-disciplinary teams of different stakeholders with diverse backgrounds to create strategic solutions and design sustainable strategies to Luxembourg's transition to a low-carbon resilient future. The key themes that emerged in the 2050 vision include circular economy with an emphasis on resource efficiency and waste reduction beyond decarbonization according to the final manifesto in the project's final publication.

Since the term transition can embody different meanings, and it reflects multiple understandings and ideas regarding its scope and extent, in this thesis it refers to a multilevel (social-ecological-technical) systemic change from linear structure economy to a regenerative / net-positive circular structure economy approach of sustainability in the built environment.

2.2.6 Circularity in the built environment: key concepts

While the principles of circularity can be applied to a full range of industries and processes, their integration into the built environment have had positive connotation especially in terms of sustainability, and the evolution of their applications in engineering has come a long way since the coining of the term.

In the context of urban development and construction, circularity involves rethinking how structures are designed, constructed, used, adapted, and eventually deconstructed. By adopting circular strategies, the built environment can significantly reduce waste, conserve resources, enhance the flow of materials and resources in the system and create more sustainable and resilient cities [183], [184]. Transitioning from a linear to a circular model in construction not only addresses environmental challenges but also offers economic and social benefits. There is a multitude of circular design concepts and strategies related to the built environment and construction industry, and some are discussed in this chapter.

2.2.6.1 Materials

2.2.6.1.1 Buildings as material banks

Within a CE framework, each component of a building possesses an inherent value. It is a fact that in business-as-usual scenarios, these elements end up typically discarded or downcycled at the end-of-life stage of a built structure. The European Commission estimates that despite the high potential, the level of recycling and material recovery of construction and demolition waste fluctuates extensively across the EU ranging from less than 10% to more than 90% [185], and if one fact can be concluded from the numbers, it is that recovery is possible. On the other hand, for this recovery to function it has to take many forms and not only downcycling, because when buildings are demolished in a conventional destructive way, demolition waste produces recycled aggregates that face major challenges of suitability and strength [186] when used in concrete if not treated mechanically, thermally, or chemically [187], and the recovery process itself in recycling plants produces secondary waste, like screening fines and washing sludge, that remain unutilized and often landfilled, potentially disfiguring landscapes, altering soil and groundwater composition, and disrupting ecosystems [188]. While different studies explore the methods of improving recycles aggregates, the best ways to avoid waste is by not creating it in first place, and these design concepts will be discussed in the next section.

The concept of buildings as material banks entails viewing those as repositories of all sorts of materials that can be reused, repurposed, or upcycled to become new products in new projects [189]. These elements and materials then become resources for future constructions. However, the accurate documentation of material databases, along with records and bills of quantity, is essential to facilitate this process [190].

As quantifiable objects, material stocks databases, together with certain circularity indicators, could further aid in understanding the degree of circular economy implementation [191]. Material composite indicators are often used for calculating material stocks, and researchers have worked on developing resource cadasters for building material stocks in various regions to provide essential databases for determining the available pool of resources and predicting potential actions for the circular supply of resources. [192]

In a recent study of the Luxembourgish existent structures, potential construction demolition waste was quantified through a geospatial material stock quantification method, and concluded that the overall mineral materials embedded in construction in the country sum up to 276.75 Mt accounting for 450.8 tons/capita, and that the construction demolition waste generated from the existing building stock is expected to be up to 226.9 Mt by the year 2100, and as high as 885.3 Mt if future growth building scenarios are considered [193]. Therefore, viewing buildings as material banks offers a new perspective on construction waste and its value, shifting how a building is imagined from conception to disassembly through its whole lifecycle.

Another main idea on the use of existing material stocks includes the possibility of their use in the construction of affordable housing through selective deconstruction or soft stripping of structures at the end-of-life stage [194], thus forming a strong link between social and technical aspects of circularity.

2.2.6.1.2 Local sourcing

The importance of local sourcing of virgin materials or reused elements is mostly related to lowering the logistics related emissions that arise with the extraction, production, and transportation of such materials [195], in this sense, using materials of local or regional origin helps to minimize environmental impacts and promote sustainability at the same time [196], as well as keeps the potential impact local and therefore easier to manage, recognize, and resolve.

2.2.6.1.3 Responsible and healthy materials

The increased focus on responsible and healthy materials to mitigate environmental and social impact can also be considered as a circular principle, especially that various researchers have highlighted the importance of eco-friendly building materials of natural or recycled origin that are light, non-destructive, and energy-efficient in certain lifecycle phases when compared to conventional construction materials[197], [198].

The integration of sustainable materials into construction practices is an important step towards their aligning with CE principles. Sustainable materials, such as wood and other bio-sourced materials, have positive climate impacts, including CO_2 storage and lower energy intensity during production [199], on top of the characteristics cited previously. It is important to emphasize that such materials are not only related to structural and load bearing elements but also for non-structural functional materials such as insulation fillings, floor coverings, façade elements, etc.

Many researchers have studied wood and composite structures to mainstream such materials into the construction industry, and in Luxembourg specifically, the research by [200], [201], [202] creates valuable input towards a direction of encouraging the use of composite materials as a means of sustainable practice. In a study focusing on the health aspects of construction systems, the research conclusions drawn showed that programmable construction systems can tailor chosen materials to meet specific health and sustainability requirements by incorporating such priorities into construction processes, and by doing this a shift is created towards future constructive systems that support the principles of CE [203].

2.2.6.1.4 Urban mining and material cascading

As an extension of the concept of buildings as material banks, urban mining is the process of reclaiming raw materials and resources from existing urban environments primarily from existing buildings to extract valuable materials that are no longer in use. This approach can contribute to circularity by keeping materials in the loop longer and reduce the environmental impact of traditional mining [204]. By treating the built environment as a source of reusable materials, urban mining helps reduce the need for new raw resources. However, some studies show that recovered materials are sometimes contaminated with toxins, synthetic adhesives, or coatings, and some building components, like composite materials, are difficult to recycle with current technology [205]. While urban mining offers a more resource-efficient approach, it remains a temporary step toward a fully circular construction sector and cannot, on its own, resolve the future demand for sustainable building materials.

Complementarily, the concept of material cascading in which materials are reused in a series of applications, typically involving less quality at each use until those cannot be used anymore, also serves to prolong the lifecycle of materials, and maintain resource efficiency, but again faces the limitation of materials retaining value and function at each use. Eventually the material in question cascades to the last stage of its lifecycle reaching a state where it can’t be effectively used anymore and becomes waste [166].

2.2.6.1.5 Carbon storing including bio-based materials

There are many types of carbon storage techniques that are available in the built environment. One recent study by *Kuittinen et al.* [206] mapped and classified existing technologies for carbon storage into 13 typologies based on 3 approaches linked to the location of the capture and storage: off and on the site (Figure 22).

Biobased construction materials are used for many purposes, one of which is their carbon sequestration properties. Wood is considered a key biobased material due to its potential in carbon sequestration especially when sourced from sustainable forestry, and in uses where its emissions are balanced over its lifecycle, particularly when reused or recycled, so that at the end-of-life stage the carbon is still in the cycle and not released [206], [207]. Other biobased materials that present carbon storage potential include bamboo, straw, and hemp.

Another mean of carbon storage is the CO_2-cured concrete. During the process, CO_2 captured from different sequestration technologies is used in concrete curing through a reaction in which the alkaline minerals from the concrete containing calcium or magnesium react with CO_2 to form carbonates [208]. This mechanism is similar to the natural process of carbonation in concrete where CO_2 from the atmosphere reacts with calcium hydroxide ($Ca(OH)_2$) to form calcium carbonate ($CaCO_3$).This reaction strengthens concrete over time and can absorb a portion of the CO_2 emitted during cement production [208], although there are questions on the potential absorption and if it is realistic due to factors like lack of air contact in buried concrete for example, and the carbon-intensive production of cement and limitations on maximizing carbonation in certain structures. Other factors that influence the absorption potential of concrete are material properties, exposure to air, and time, with outdoor and sheltered structures absorbing more CO_2 than indoor ones [206], [209].

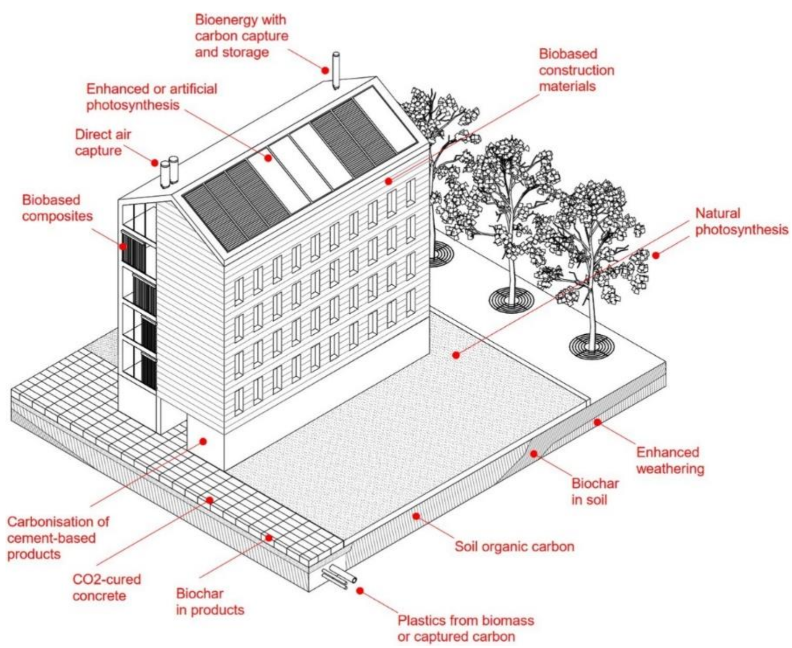


Figure 22. Carbon storage means in the built environment [206].

2.2.6.2 Structures

2.2.6.2.1 Design for adaptivity / adaptability

As our society changes and the uses of buildings need to respond to these many changes that occur, the structures that compose our built environment have also to adapt to fulfil these transformations [210]. Adaptability has been looked at from the CE perspective in many ways since it allows to accommodate change in an affordable manner and reduces drastically the amount of possible waste generated from these changes, thus playing a role in reversibility of built products in the reversible chain, a key concept of CE [211]. Various determinants of circular building adaptability were the object of research of an integrative literature review by Hamida *et al.* that summarized those into ten categories [211]:

1. Flexibility / adjustability
2. Generality / multifunctionality / versatility
3. Elasticity / expandability / scalability
4. Movability / relocate-ability
5. Dismantlability
6. Convertibility / transformability
7. Recyclability / reusability / disaggregatability
8. Refit-ability
9. Accessibility / availability
10. Modularity / regularity

All these design determinants have been concluded to be channels of incorporating circularity and adaptability in the built environment according to the studied literature.

Unlike other circular design pathways that heavily rely on the planning phase design before a building has come to life, certain elements of adaptability are widely suited even for old buildings. The case for adapting old idle buildings to new functions that revitalize neighborhoods and create environmental benefit as well as social and economic development is amply discussed among architecture and economics scholars and specialists [212], [213].

2.2.6.2.2 *Design for disassembly and deconstruction*

In a similar way to adaptability, and for some authors even a determinant of it [211], disassembly is part of the circular strategies in the built environment, and can be defined as design principle in which a deconstruction process to remove structural or non-structural building components part by part without causing damage can be carried out, and thus facilitate their posterior use in a new or existing building [214].

An important concept for disassembly is the one of "shearing layers" where a building or a structure is seen as a superposition of material layers that are strongly linked to one another (Figure 23). This idea of a looking at a building as a system and not as a homogenous block of matter paves the way towards understanding how different parts of that building need different care at different times and has the power to inspire a new way of thinking when designing each of these layers. The term shearing layers was coined by the architect Frank Duffy in 1992 and later expanded by Steward Brand who added the site and the skin as components to the 4 initial elements that were the structure, the services, the space plan, and the stuff [215]. While this concept has a positive effect on the because designers would consider the life cycle of the materials and installations used in each layer, it is a limited concept because it is oriented only towards the physical configuration of a building while other spatial aspects are disregarded [210].

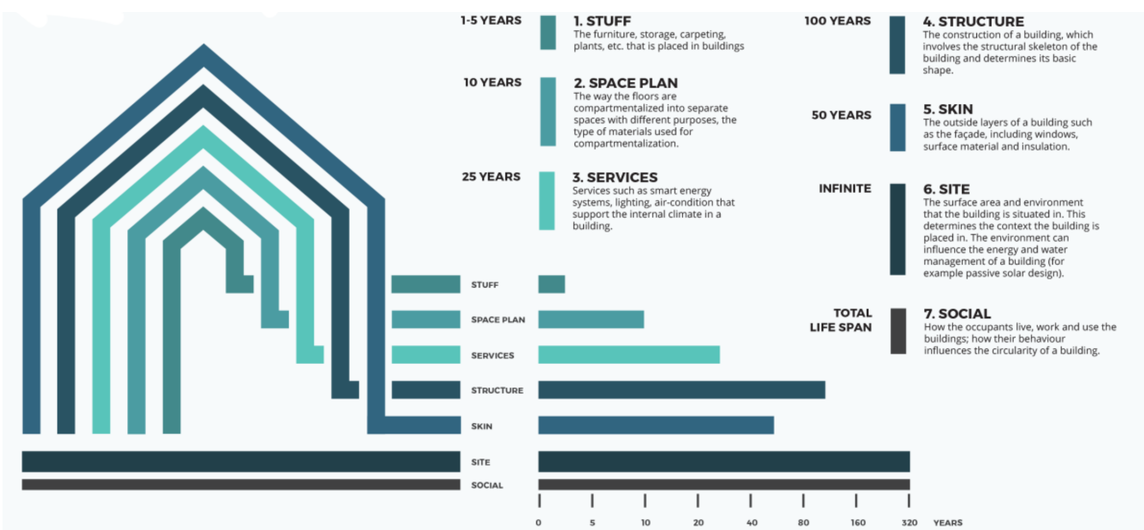


Figure 23: The layers of a building illustrated according to the Brand model [216].

In the report by the World Business Council for Sustainable Development entitled The Building System Carbon Framework, the authors add a seventh element to the initial concept of shearing layers that runs throughout the whole lifespan of a building: the social element (Figure 23). By acknowledging the impact that the lifestyle of the occupants as well as the use of the buildings has on all those previously defined layers, an important influence on circularity is accounted for.

There is a vast literature on design for deconstruction and reuse [217], [218], [219], [220], and other concepts besides the layering approach that constitute design enablers for this practice, such as avoiding secondary finishes, the use of bolts and screws instead of glues, avoiding certain composite materials, modular construction, etc.

As a building approaches its end-of-lifecycle, there are a few options to consider. However, the degree of circularity varies from one approach to another. For example, if a building is not designed for disassembly, selective deconstruction with the purpose of future use can still represent a more sustainable alternative to traditional demolition where the totality of the building layers is downcycled [221]. This is an example of a partial circular strategy, that although is beneficial to reduce the end-of-life impact for old buildings that are not designed for disassembly, carries on further into the future as long as the status quo considers recycling as a circular concept.

2.2.6.2.3 Design for durability

Durability is a parameter that is mostly centered around the design of built structures that last longer, therefore minimizing future waste generation and emphasizing the R-strategies (reuse, repair, recover, regenerate, etc.). It could be material, structure, or process related when thinking of a built infrastructure. To give an example, in a study performed on the effect of repairs and replacements of different floor coverings [222], the comparison concluded that the material used as well as its longevity played an important role in the life-cycle assessment outcomes favoring inorganic coverings such as natural stone or ceramics over others due to their durability, despite the manufacturing phase emissions being higher than for other materials. Durability is also an intersectional parameter with other circular concepts such as design for disassembly, since deconstructing for reuse requires that a structure is still in a useful condition and that its elements are durable for future uses [205].

2.2.6.2.4 Retrofits and refurbishments

Retrofitting refers to the process of adding new technology or features to older systems or structures to adapt them for a purpose. This is often done to improve energy efficiency, enhance safety against earthquakes, or comply with new regulations such as the EU Directive on the Energy Performance of Buildings that aims to improve the energy performance of buildings through a set of measures. Retrofitting can apply to various contexts in the built environment and relates to circularity through actions that tend to prolong the lifespan of a building and make it more sustainable in a way. [223]

Similarly, refurbishment involves renovating and restoring something to an improved condition with or without adding new technology and it is commonly used in the context of buildings including minor or major works. Renovation and remodeling are also design concepts that relate to the same concept from the circularity point of view.

In their study on adaptive reuse of existing buildings, authors Aigwi et al. note that it takes approximately 65 years for newly constructed buildings to recover the lost energy from demolishing existing buildings [224]. Where this can be a contested number it shows how important it is to address materials and change design as well as the importance of refurbishment. Even if most new buildings were to be conceived as circular modular prototypes, there would still be a need for new materials or at best reused elements or recycled materials. Even if we change the way we design and construct and occupy structures today, there is still a backlog of every constructed conventional building's material cycle in the loop that might just become waste if the option of refurbishment is not considered. Moreover, a structure that is kept in good shape is considered to be an asset, especially in the case of material circularity concepts such as viewing the built environment as a valuable material bank.

2.2.6.3 Digitalisation

2.2.6.3.1 Material passports

Strongly linked to the idea of buildings as material banks is the material passport for circular buildings which allows for a better understanding of the circular value potential of the built system and its constituent elements through a reliable base of information. These passports serve as a means to enhance transparency regarding the materials used during construction and / or renovation by simply providing clear information about these materials, which has a number of benefits including a reduction of costs associated with investigating hazardous substances before demolition as well as improving asset management of buildings, as public authorities will have better insights into materials and their potential for reuse [225].

The overall objective of having material passports is to maximize the reuse potential of all materials which starts with the shift in design process and is then assisted by this detailed data set [205]. The more accurate the representation, the higher will be the future reuse potential [225]. However, material passports alone are not sufficient to manage flows through the system as a stand-alone concept, standardized and centralized platforms are required for the registration of such passports for an effective circular resource management in the built environment [205].

Certain platforms such as *Madaster* and *CirCon4Climate* already exist in many European countries, where a material cadaster is at the center of an inflow of information coming from BIM (Building Information Modeling) or other databases. There is a common consensus among such companies that the benefits of the material passport concept outweigh the cost related to implementing it in the long run.

2.2.6.3.2 Digital platforms

Digitalization or virtualization is part of the pillars of frameworks of transition towards sustainability through CE, such as in the *ReSOLVE* framework proposed by the *Ellen McArthur foundation* together with *Arup* [226]. For them, virtualization is about displacing resource use with virtual use, replacing physical products and services with virtual services, and delivering services remotely. The digitalization principle overlaps with many others such as durability, when it concerns using digital services to facilitate real-time maintenance, and circular design, through Building Information Modelling (BIM) that allows efficient collaboration between all stakeholders throughout the full life-cycle of an asset.

One good example of digitalization in this context is the Digital Deconstruction project [227] supported by *Interreg* North-West Europe in which partners created smart services to make circular construction possible through developing an innovative digital decision support system integrating different digital tools to help define the most sustainable deconstruction strategy for a building. Just like the idea behind material banks and material passports, this project delivered, among other outputs, an open-source software system that allows engineers to track and reuse materials originating from deconstruction and dismantling projects.

2.2.6.3.3 Product Circularity Data Sheet (PCDS)

The Product Circularity Data Sheet (PCDS) is the product of a system designed to provide transparent and verifiable data on the circularity of products. Its purpose is to facilitate the sharing of trustworthy information about how products are designed, manufactured, and managed to support CE principles. The PCDS offers a standardized format for presenting this data without scoring or ranking products. Luxembourg's ministry of economy has started the implementation of this initiative with the objectives of providing stakeholders with this essential circularity data, improving data sharing efficiency across supply chains, and encouraging enhancements in product circularity performance [228].

The PCDS system consists of three key components: a data template containing standardized statements about product circularity, a third-party verification process to validate the content, and a decentralized data exchange protocol. It connects to circularity by ensuring transparency along the supply chain and giving each product or component its own digital identity and describing its circularity characteristics. It also aligns with ISO standards (ISO/NP 59040) and international/EU regulations. Manufacturers are responsible for creating, managing, and updating PCDS documents at each stage of production, ensuring that any changes are accurately reflected.

The primary audience for the PCDS includes manufacturing companies and stakeholders involved in circular business models. According to the Ministry of Economy of Luxembourg the PCDS is part of the circularity policy of the country and aims to establish a common language for describing circularity, save costs by providing standardized information, support the design of circular products, and facilitate cost-effective circular business models.

In Luxembourg, the model supplied by the Ministry of Economy includes data on (1) product and company or manufacturer identification, (2) the composition of product constituents such as chemical substances present, sourcing, and recycled content, (3) circular design relevant characteristics such as design for maintenance and repair, disassembly, dismantling, safe operation, reuse.

2.2.6.3.4 BIM (Building Information Technology)

To complete the discussion on the role of material passports, technology, and circular design, BIM models become an important part of the topic especially with the need for good systems of information management and having comprehensive data on the quality, technical specifications, and measurements of building materials and components.

BIM in its simplest form is often seen as a 3D model containing information, but it is more than that—it's an activity and a process of managing various types of data across different project phases. One of BIM's greatest potentials is within the circular design framework, which focuses on the reuse of building materials, and it supports this by enabling detailed documentation of materials and their specifications. The integration of this information and material passports with BIM provides the information needed to support decision-making in a CE. Different types of BIM models can be used depending on the project phase such as the design phase, construction phase, built/in-use phase, and a lifecycle mode focused on circularity and long-term use aspects [229], [230], [231], [232], [233].

2.2.6.4 Standards and certifications

2.2.6.4.1 Building certifications

In the built environment, assessing the sustainability of structures involves using a wide array of tools designed to estimate how green or sustainable a building is based on specific criteria, with an array of criteria ranging from environmental to ecological, social, and technical characteristics. Globally, there are over 600 certification systems [234] that provide ratings or grades, each reflecting the degree to which a building meets the sustainability standards set by that specific tool in question. These certifications encompass various aspects of sustainability, offering a framework for evaluating and promoting environmentally responsible building practices.

The diverse certifications have different rating systems and categories which makes the complexity of assessing or evaluating sustainability even more difficult to compare across buildings and certifications. Research has been mostly focused on the benefits of such certification tools, comparative analyses between them, and on studying what areas do these certification tools cover or leave out [234], [235].

In the absence of a global set of benchmark parameters, the levels of comparability and the differences in gradings, scoring, and weighting make it even more challenging to make sense of the labels and ratings. A study by BRE Global [236] comparing various international certifications such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) concluded that there are significant degrees of variation between the systems for the same grade than might otherwise be expected. As an example, a LEED Platinum and a BREEAM Excellent or Outstanding, the top categories of each certification respectively are not equivalent in terms of sustainability features or environmental impact according to the study. For example, the study concluded that if a United Kingdom building is designed to conform to LEED criteria, the maximum rating it would likely achieve with BREEAM is Good.

The discussed so called green assessment tools, like LEED, BREEAM, and others, were originally conceived as voluntary market mechanisms to help building owners improve and communicate their environmental performance [237]. These tools are designed to drive market transformation by creating competitive advantages for high-performing buildings. Despite the substantial increase in LEED projects and the resulting environmental gains, these measures are still considered insufficient in addressing the scale of the building sustainability problem as widespread adoption is still a challenge.

In Luxembourg, a sustainable building certification called LENOZ (Lëtzebuerger Nohaltegkeets-Zertifizéierung) is a nationally promoted certificate for residential buildings, introduced by the government and regulated by law, albeit not obligatory [238] .It promotes elements of sustainable construction by assessing six different categories and classifying the overall performance of a building in classes from 1 to 4 according to the level of compliance with those defined categories, and is used as an eligibility criterium for the obtention of governmental financial support.

2.2.6.4.2 ISO Standards

2.2.6.4.2.1 *Life Cycle Assessment (LCA) - ISO 14040:2006 & ISO 14044:2006*

The Life Cycle Assessment (LCA) methodology has evolved significantly since its inception and plays a central role in assessing the environmental impacts and resource consumption of products throughout their entire life cycle. Initially formalized in the 1990s through standards such as ISO 14000, LCA has become a key tool for environmental management across various industries [239].

As an important part of circularity, LCA is key in understanding the environmental consequences of a product's entire lifecycle and quantifying those, which helps identify opportunities to extend product life, reduce waste, and close material loops. LCA standards ISO 14040 and 14044 were the pioneers to provide frameworks for assessing the environmental impacts of products and processes throughout their entire life cycle—from raw material extraction to disposal [240], [241]. From the point of view of material circularity, it is also a useful tool as it models full lifecycles with the possibility of changing parameters easily and comparing with other existing or hypothetical solutions. However, it is mostly centered around environmental impact categories with climate change potential in $kgCO_3\text{-}eq$ being the most known metric, as well as land and water use, which limits its scope to a strict environmental perspective.

2.2.6.4.2.2 *Circular Economy – ISO 59000 family*

The new family of standards published by the International Organization for Standardization (ISO) in 2024, developed with input from over 100 countries, can be considered the first standardized international guidelines and definitions for the CE [242]. The ISO 59000 family provides a common understanding of the CE and sets out guidelines for business operations within this model.

According to ISO, the standards aim to help companies of all sizes and industries transition to circular business models, which can involve redesigning products, optimizing processes, or adopting new recycling and reuse strategies by providing a structured approach for organizations looking to integrate circularity into their operations.

Not specifically designed or conceived for the built environment or construction industry, ISO 59000 defines six core principles of sustainability like the British standard [165] discussed in the definitions of circularity. Those are: systemic thinking, value creation, value sharing, resource availability, and ecosystem sustainability. In rethinking processes and business structures as well as aligning this set of new norms with European sustainability initiatives and recognizing that transitioning to a CE may require significant changes, it brings new topics beyond the technological and environmental elements into the discussion around circularity.

2.2.6.4.3 Other certifications

2.2.6.4.3.1 The Living Building Challenge

The Living Building Challenge (LBC) is a certification program developed by the International Living Future Institute that represents a transformative approach to building design and construction by shifting from minimizing harm to actively contributing to a regenerative, sustainable future as defined in the program manual [243] . It promotes the idea of humans as stewards of what they refer to as a *living future* urging stakeholders to design and build in ways that positively impact both natural ecosystems and human communities. With a mission to restore the relationship between people and nature, the LBC combines philosophy, advocacy, and certification, to challenge how aspects of design and construction are approached.

As a certification program it encourages a paradigm shift in the industry by presenting design and construction as opportunities to enhance biodiversity, social equity, and cultural richness, and is structured around seven key performance categories, called petals (Figure 24). These are place, water, energy, health and happiness, materials, equity, and beauty—each containing Imperatives that set specific requirements. Projects seeking certification must meet performance-based standards over 12 months, and this approach can according to the institute ensure actual sustainability rather than just anticipated outcomes.

The LBC's holistic approach applies to all types of projects, from new buildings to renovations, interiors, and landscapes. It emphasizes adaptability to regional conditions, pushing for solutions that align with the local environment. The program also calls for urgent, large-scale change in the built environment to address climate and ecological crises, inviting professionals and society to envision and work toward a future that is socially just, ecologically restorative, and culturally enriched.

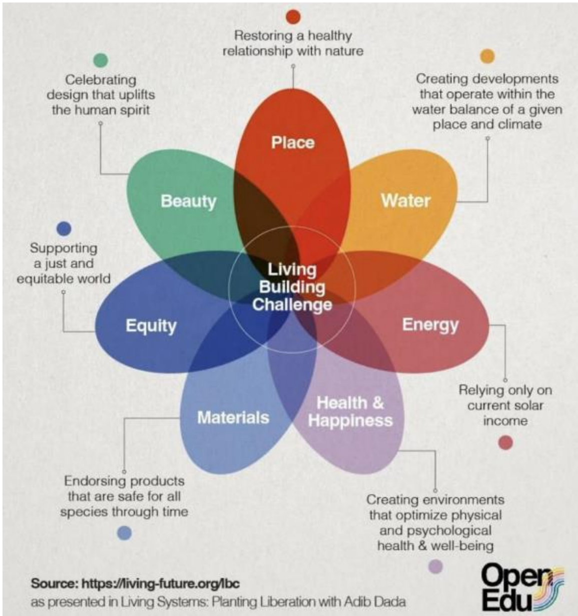


Figure 24. The petals of the Living Building Challenge standard. [244]

2.2.6.5 Regenerative systems and design

Sustainability practices in the built environment and concepts such as green buildings, the use of recycled materials and implementing energy efficiency measures often aim to reduce harm to ecosystems by creating improved alternatives to traditional linear practices. However, these approaches are only a first step towards regenerative practices that aim to go beyond doing no harm into a vision that involves active contributions to restoring social-ecological systems through positive action [245]. The previous parts of this section zoomed in on circular practices that can be considered steps towards a more sustainable and greener built environment, but those practices isolated are not likely able to respond alone to the complexity of the ecological and environmental problems that we face because they do not offer a systemic solution that accounts for complexity [245], neither are they sufficient for the magnitude of change required to achieve global sustainability because this calls for transformational change that goes beyond net-zero [246].

One familiar metric that makes the case for the regeneration of ecosystems is the Earth Overshoot Day which is the date at which humanity's need for resources exceeds what the earth can regenerate in that same year. In 1971 the day fell in December, and this year in 2024 the date falls in August, roughly 4 months earlier, meaning 1.7 earths are needed to fulfill our current needs *ceteris paribus* [247]. The current scenario on the impact of human activity suggests that more than 1 million plant and animal species might face extinction within the next few decades unless serious efforts are made to reverse the intensity of drivers of biodiversity loss [248].

2.2.6.5.1 The theoretical background of regenerative design

Although the construction sector in many aspects has yet to break through from linear practices in first place, several authors have already started to study and research the sustainability transitions from green to regenerative design. To understand this concept better one can, look at some definitions of what regenerative means according to different authors. The idea of regenerative systems is strongly connected to having social-ecological worldviews in which humans do not exist in separation with nature, and is not only, limited to the built environment.

In the built environment, regenerative approaches are essentially about rethinking the roles of such environments and the design process, especially when it comes to how is this design process guided and which questions are asked during this process [249], it is also defined as a concept that is beyond the classic understanding of sustainability (Figure 25) with the three pillars, that goes beyond mitigation and balance, and in the construction industry an approach that emphasizes actively restoring resources while adapting to the changing demands and challenges of said industry [250]. According to Reed [251], a regenerative approach is a strategy focused on achieving genuine sustainability promoting continuously evolving living systems that benefit all participating stakeholders. Complementarily, Du Plessis [252] describes the regenerative paradigm as a transition from a mechanistic to a living systems approach, that focuses on engaging with the living world and fostering a mutually beneficial relationship with nature through adaptive and resilient strategies.

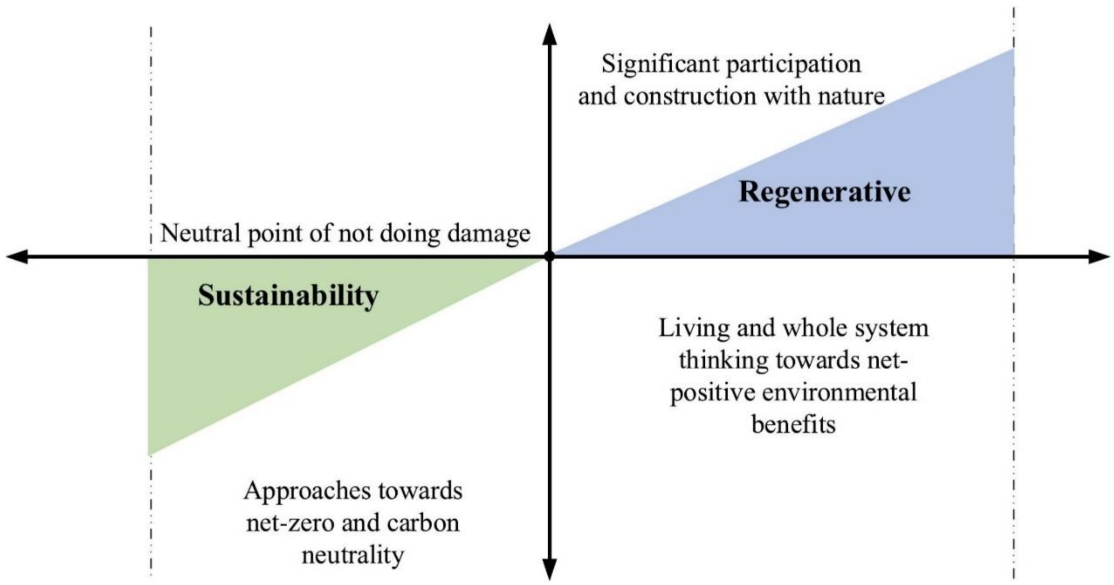


Figure 25. Sustainable vs. regenerative design [250].

To understand better the origins of such a concept, Table 7 encapsulates the core theories and their implications for regenerative design practices emphasizing the importance of social dynamics, natural interactions, and complex interrelations in the built environment according to Oyefusi *et al.*'s overview on regenerative design theory [250].

Table 7. Theoretical Origins of the Regenerative Concept [250].

Theory of Regenerative (Design) Concept		
Social Constructivism Theory	*Living Systems Theory*	*Complex Systems Theory*
Based on the collaborative creation of knowledge and how individuals actively contribute to shaping their social realities seeing occupants as learners in communities that integrate cultural and societal insights and reveal their interconnectedness within built environments.	This theory highlights the existence of a co-creative partnership between human systems and nature. Important points include understanding life dynamics, focusing on practices that highlight resilience, adaptation, and a partnership with nature, thus viewing humans and nature as interconnected, facilitating a shift towards net-positive environmental outcomes.	Viewing the built environment as a dynamic entity, this theory addresses the intricate interconnections within the construction industry, seeing it as encompassing complex interrelationships among physical, biological, and behavioral patterns in a socio-ecological system, that requires concepts and strategies to navigate uncertainty inherent in complex systems.

According to Cole [253], shifting from green to regenerative design implies significant conceptual and practical changes, including redefining the role of tools to support this transition and asking the question if a regenerative approach can catalyze the necessary changes more quickly than the current options such as green design.

In the built environment, in contrast to sustainably designed buildings, regenerative buildings are designed and operated to reverse ecological damage and have a net-positive impact on the natural environment by being conceived as integrated parts of the ecosystem rather than just stand-alone structures that reduce resource use and save energy and water. Shifting from a sustainability lens to a regenerative one means that architects should question how we can design structures that not only use limited resources but also restore them as discussed previously in the definitions of regenerative approaches. Regeneration also seeks to facilitate a more resilient environment that can resist natural challenges.[237], [254], [255]

In this context, it is not enough to aspire to mitigate the effects of human activity. On the opposite, societies need to increase the carrying capacity beyond pre-industrial conditions to generate ecosystems functions and services to reverse the current ecological footprint trends. This approach is promoted through the regenerative paradigm that seeks to develop renewable resources infrastructure and design building with a positive environmental impact [254].

2.2.6.5.2 Transition pathways

To illustrate in a model, what a regenerative framework looks like, a paper by Buckton *et al.* [256] introduced the regenerative lens (Figure 26), a cross-disciplinary framework based on research that highlights that regenerative systems promote ongoing cycles of wellbeing between humans and nature, creating self-sustaining life. The framework outlines five key qualities necessary for such systems: an ecological worldview, mutualism, diversity, agency for both humans and non-humans to act regeneratively, and continuous reflexivity. The authors apply this framework to a future food system to demonstrate its usefulness for guiding reflection and driving ambition toward regenerative practices, but it can be translated to other systems and sectors since its values are universal and applicable in the construction industry.

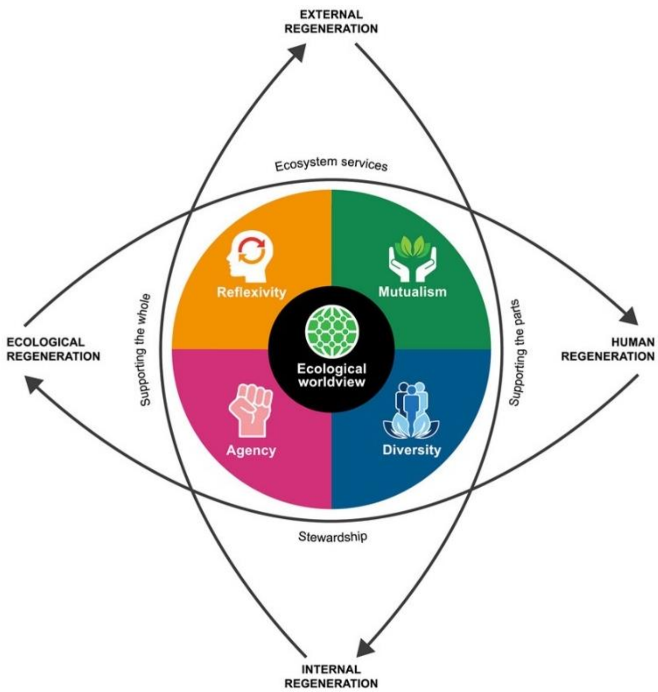


Figure 26. The regenerative lens. [256]

Circling back to the built environment and given the differences between the design approach discussed earlier in this section to the actual reality of the construction sector, it becomes clear that transitioning from traditional to green to regenerative design necessitates a fundamental shift in how a building's function and performance is understood. This involves addressing several key relationships:

(1) As conceptual shifts bring practical implications, a change in the way of thinking and designing that emphasizes holistic, systems-level thinking over isolated, reductive strategies becomes necessary to ride away from reductive approaches.
(2) The relationship of buildings in a setting, one that recognizes that structures are embedded in a larger context and recognizes the impact of individual built structures within their broader environmental and social contexts.
(3) And finally, the scale aspect of the system in question, creating ways of balancing place-specific approaches with global sustainability goals.

The most significant change required for this transition is a shift in mindset among stakeholders. This involves moving from a worldview that sees humans as separate from and dominant over nature, to one that recognizes their interdependence with natural systems. On the solution level, tools and frameworks that promote innovative design solutions are considered essential in facilitating this shift [237].

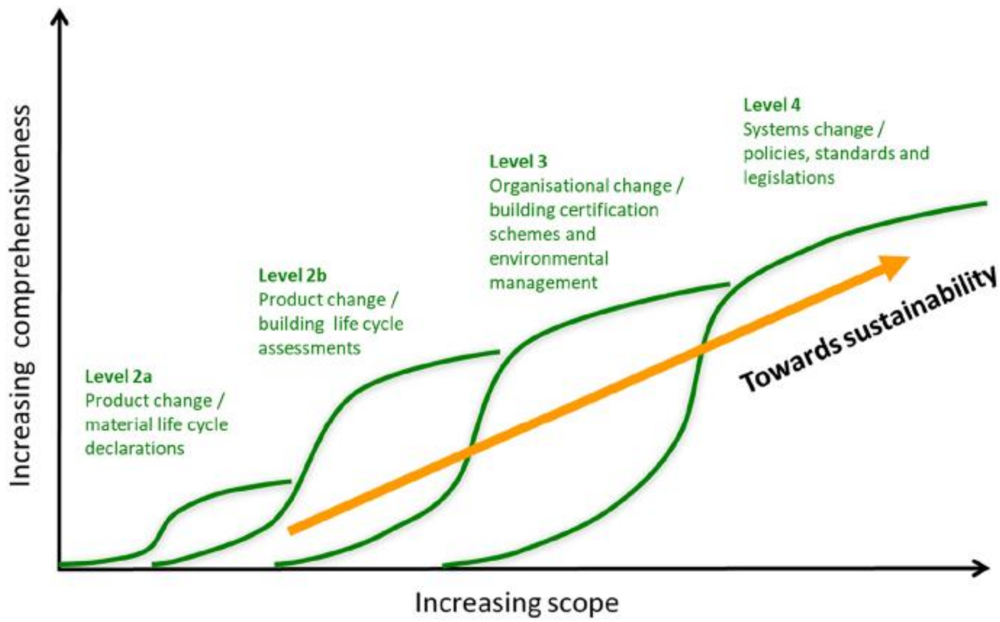


Figure 27. Systematic change towards circular economy for the construction sector at different systemic levels [257].

One of the key implications of regenerative design according to [237], and that is relevant to this research since it studies stakeholder connections, is the establishment of common ground with diverse stakeholders where an expansive dialogue of regenerative design can help engage and maintain commitment from a broader range of stakeholders. Regenerative design requires designers and users to adopt a whole-system perspective, integrating social and environmental strategies within this broader context.

These implications have the potential to reframe the nature of design and the role of designers, steering the profession toward a more holistic and integrated approach to sustainability [253], until higher levels are reached as the scope increases and the comprehensiveness with it (Figure 27)

2.2.6.5.3 The regenerative or nature-positive circular environment: an example.

To give an example that illustrates the concept of regenerative CE (Figure 28), the research by *Benites et al.* [258], builds up on the concept of the doughnut economics by *Raworth*, and integrates elements of CE and regenerative design naturally. It is built upon five key pillars: (1) circular metabolism, promoting resource regeneration and equitable distribution; (2) adaptive-resilient urban systems, ensuring livability, accessibility, and safety in response to future challenges; (3) healthy, bio-connected ecosystems, fostering human-nature relationships and supporting nature-based solutions; (4) good governance and thriving communities, advocating inclusive management of social, economic, and environmental capital; and (5) a systemic approach with positive impact, incorporating life cycle thinking and respecting ecological and social boundaries.

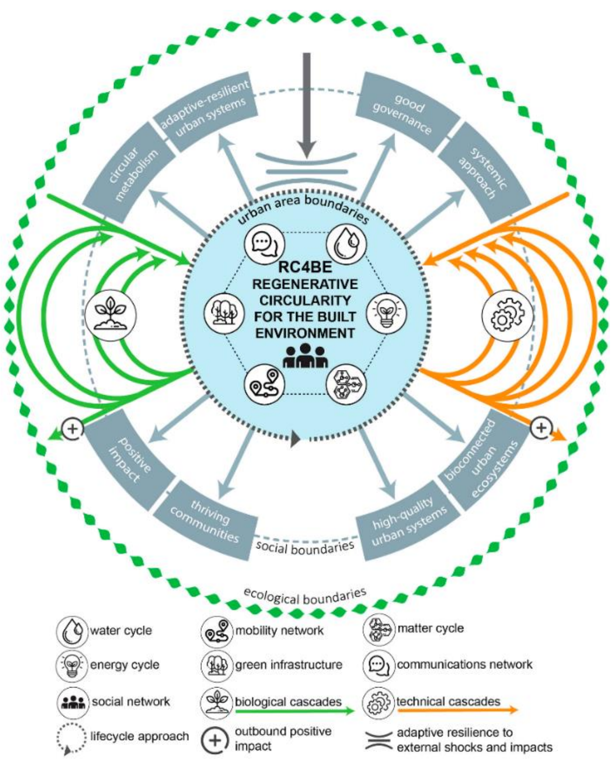


Figure 28. A conceptual model of representation of regenerative circularity in the built environment [258].

2.2.6.6 Alternative business models

The circular economy marks a departure from traditional linear business models, which rely on a "take-make-dispose" approach. To enable this shift, circular business models prioritize sustainability and resource efficiency as key drivers of circular strategies. These models emphasize the entire lifecycle of materials and incorporate "R" strategies—such as reuse, repair, remanufacture, and recycling—to maximize value retention. This transition requires businesses to fundamentally rethink how they generate value, focusing on closed-loop systems that reduce waste, minimize environmental impact, and promote long-term economic and ecological resilience. For example, innovation in materials, decoupling economic growth from resource extraction, narrowing and closing loops, are all examples of used business models that are alternative to traditional linear methods [259], [260], [261].

Table 8. Examples of potential circular business models in the built environment.

Types of circular business models	Application in the built environment
Circular Inputs	Focuses on using renewable, recycled, or sustainable materials (inputs) in the production process to eliminate waste. Businesses can turn waste into an asset by repurposing it, such as using industrial by-products in new applications just like the material concepts studied by project CO2REDRES, when applied to a business plan for instance.
Sharing Economy	The sharing economy model encourages businesses to share idle assets, like construction machinery, with other companies. This approach optimizes asset use, reduces the need for purchasing new equipment, and sometimes can lower costs depending on the asset in question.
Product-as-a-Service	As a model that has product lifecycle extension and reduction or elimination of potential waste, it offers product as a service rather than owned property. The company retaining ownership is then responsible for maintenance and upgrades, and proper disposal. In the built environment this can apply to many elements of structural and non-structural nature depending on the conceptual design.
Product Use Extension	This model focuses on prolonging the lifecycle of products through repair, upgrade, reuse, and other modalities thus reducing the need for new production. In the built environment this can be seen as services of refurbishment and retrofitting.
Resource Recovery	A model that emphasizes reclaiming valuable materials, energy, or components from end-of-life products. The concept of buildings as material banks is in part related to this model.

The creation of effective circular business models is seen as a driver in achieving CE goals. However, the term "circular business model" has become a widely used buzzword, with diverse interpretations across academic and public discussions. While much focus has been placed on defining and conceptualizing these models, there is considerably less attention on the practical steps and mechanisms needed to transition traditional business practices into fully circular models. The latest research highlights the importance of adopting a strategic approach—encompassing data monitoring and collection, local and global collaboration, digitalization, R strategies, and innovation—for the successful development of circular business models [262]. There are several different business models that can be classified as circular, mostly a model that has circular elements to it at any level can qualify for such a nomenclature, and Table 8 gives some examples from the literature.

2.2.7 The role of public policy

Among the many dictionary definitions of policy, the *Oxford Languages* defines it as: "*a course or principle of action adopted or proposed by an organization or individual*" [263]. In the minimalism of this definition, one can already infer a relation to plans, actions, guidelines and strategies. If we were to dissect the word and go back to its origins from old french *policie* 'civil administration', via Latin from Greek *politeia* 'citizenship', from *politēs* 'citizen', from polis 'city' [264], we get to all the other dimensions that are interesting to this section: government and citizens.

Policy plays an important role in promoting different forms of change as a transition towards sustainability by regulating behaviors, creating awareness, and implementing laws to address issues that are related to the topic, such as climate change for example [265]. Various studies highlight the importance of policy in driving these transitions particularly in areas like green buildings, where policy instruments can influence a lot of aspects ranging from industry dynamics all the way to workforce shortages through cumulative incremental changes and a good coordination between policy domains and the different levels of governance [266].

Overall, effective policies that can create change without pushing stakeholders into a risk zone, are essential for creating a supportive framework that encourages sustainable practices, values innovation through experimentation, and addresses challenges holistically in various sectors to promote long-term environmental and social well-being.

While discussing the history and evolution of CE, *Tuladhar et. al* emphasized the importance of future research in advancing the CE and CE business models, identifying areas such as policy development, technological innovation, and stakeholder engagement that need to be developed [160].

2.2.7.1 Policy for circularity: EU discourse

The role that public policy plays in addressing public problems is an important one since it can facilitate needed socioeconomic transitions by promoting cross disciplinary interactions that foster sustainability. In this context the research of Zheng and Cai [199] investigated the role of public policy in fostering transformation from innovation systems towards innovation ecosystems[2] and mapped the factors that could facilitate such transition. They identified the willingness of stakeholders to engage in cross-boundary interactions as well as a prevailing sustainability ethos in the political and social value systems and an institutionalized civil society based on bottom-up approaches as factors for the catalysis of transition [199].

Some studies such as [158], present the idea that in policy, just like in practice, a focus on the technological aspect of circularity in the CE discourse primarily focuses on technocentric solutions, emphasizing resource loops, material recovery, and industrial processes, but often overlooks broader social, political, and ecological implications.

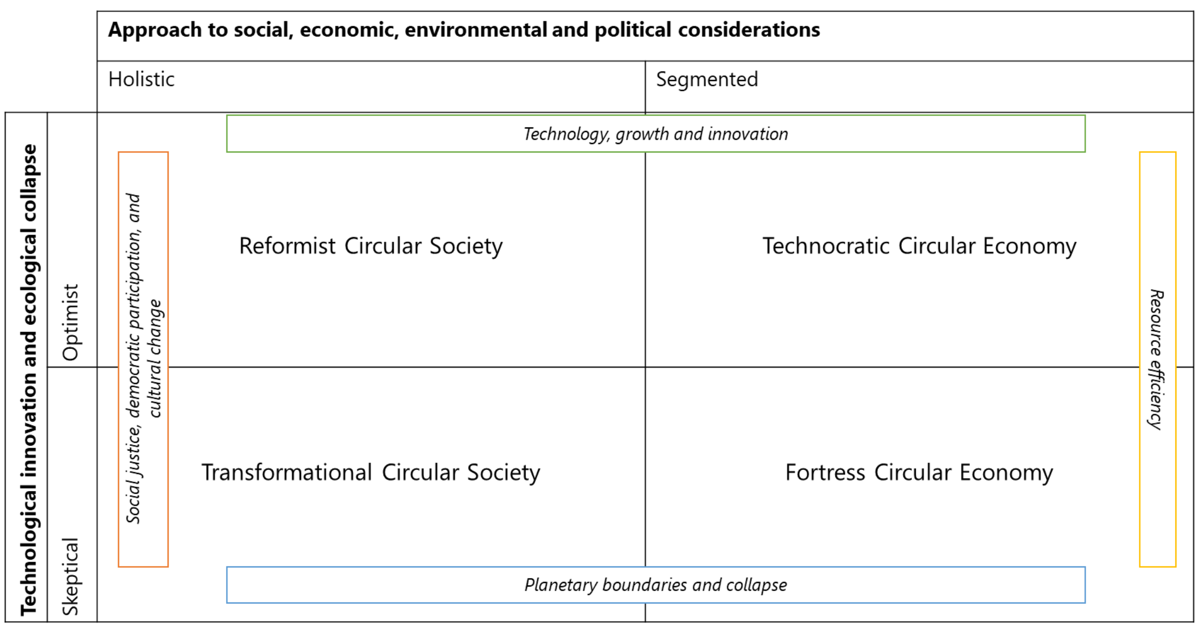


Figure 29. Circularity discourse types and the main associated keyword groups, adapted from [267]

[2] The term innovation ecosystem can be defined as: "*co-innovation networks, in which actors from organizations concerned with the functions of knowledge production, wealth creation and norm control interact with each other in forming co-evolution and interdependent relations (both direct or indirect) in cross geographical contexts, and, through which new ideas and approaches from various internal and external sources are integrated into a platform to generate shared values for the sustainable transformation of the society.*" Cai et al. [345]

In a study [267] that analyzed the discourse vs, action gap of EU policy regarding CE and concluded that there is a certain dichotomy between the talk and the actions represented by discourse and policy respectively (the discourse falls under holistic-optimist and the policy under segmented optimist i.e. technocratic circular economy, see Figure 29). Other authors also emphasized the EU strategy of current and past policies to try to reconcile environmental care with economic growth [268] or even focusing on reductive approaches such as recycling and reducing harm rather than transformative change [269]. Another important element for successful CE policy outreach is the relation to social aspects and fairness and yet those remain less recognized in both literature and policy, and are not yet properly evidenced [270].

2.2.7.2 How is the European Policy promoting circular practices?

In the same way different governments and legislative institutions are not copies of one another, policy changes in different places. In the case of the European Union (EU), one can distinguish between various types of legal acts such as regulations, directives, recommendations, etc. While they all together form the body of law of the EU and consequently influence that of its member states, some have more power than others (see *Table 9*) [271].

Table 9. Types of EU legal acts [271]

Legal act	Characteristics
Regulations	Regulations are legal acts that automatically apply to all EU countries upon enactment, without the need of being transposed into national law. They are universally binding on all member states.
Directives	Directives establish mandatory requirements for EU member states to accomplish specific outcomes, while granting them flexibility in determining the means to achieve them. Member states must adopt measures to incorporate them into national law (transpose) in order to achieve the objectives, set by the directive
Decisions	A decision is considered binding in its entirety.
Recommendations	Recommendations enable EU institutions to express their opinions and propose a course of action without imposing any legal obligations on member states. They are not legally binding.

The EU adopted its first circular economy action plan in 2015 [272] which since then got revised and updated until its 2020 version, and it was the precursor to many regulations that followed in diverse areas, including the European Green Deal that got adopted in 2019.

In his paper "*Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix*", Milios [273] describes the plurality of measures included in this action plan to illustrate the complexity of such policy and the need for an approach in policy development the favors a holistic view at systems level. He argues that the needed policy is one that looks at relevant problems and addresses them at all life-cycle levels for efficient outcome.

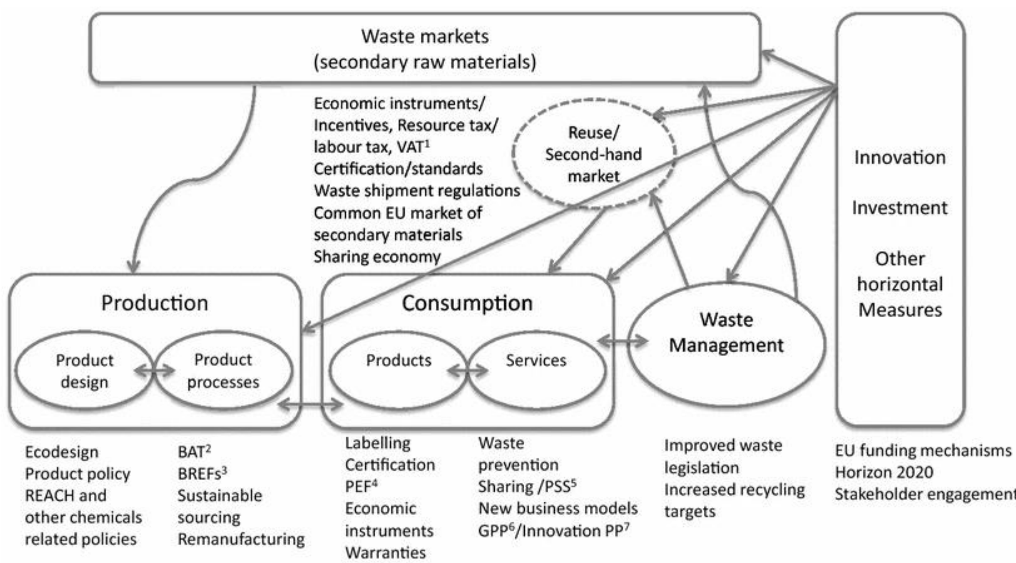


Figure 30: EU policy landscape – The plurality of measures included in the European Circular Economy Action Plan.[273]

[1] Value Added Tax; [2] Best Available Techniques; [3] BAT Reference documents; [4] Product Environmental Footprint; [5] Product-Service System; [6] Green Public Procurement; [7] Public Procurement

2.2.7.2.1 General policies

The general policies considered in this section are the EU Green Deal and the Circular Economy Action Plan

2.2.7.2.1.1 The EU Green Deal 2019

The European Green Deal is the flagship EC blueprint for the first climate-neutral continent. This roadmap aiming to make the EU's economy sustainable is a strategic document that outlines policies and actions across multiple sectors to reduce greenhouse gas emissions, enhance resource efficiency, and preserve biodiversity [274]. However, the Green Deal Industrial Plan was only released in February 2023. In the context of the construction industry including cement manufacturers and other material producers, the plan aims to simplify, accelerate and align incentives to preserve the competitiveness of the EU as an investment location for net zero industries, but specific measures to support the transition in energy-intensive industries (such as cement) until the time being have not yet been developed [12].

2.2.7.2.1.2 The EU New Circular Economy Action Plan 2020

Despite having a wide sectorial focus, in the construction sector, the EU Circular Economy Action Plan which is one of the main building blocks of the Green Deal, focuses on promoting sustainable building practices, resource efficiency, and waste reduction to support the EU's goal of climate neutrality by 2050. Key initiatives include the revision of the Construction Product Regulation to ensure sustainability in construction materials, the promotion of durable and adaptable buildings, and the development of digital building logbooks for better resource management. It also integrates life cycle assessment in public procurement through the Level(s) framework (to be detailed) and considers revising material recovery targets for construction and demolition waste. Additionally, the upcoming Strategy for a Sustainable Built Environment (expected but not yet launched) aims to enhance circularity in the sector, ensuring that buildings are designed for longevity, adaptability, and minimal environmental impact [274], [275], [276], [277].

2.2.7.2.2 Specific policies

The European Commission (EC) divides its CE policies into nine broad categories that are supported by tools and instruments to assist in implementation, spread, and follow-up actions. In this section, the relevant policies relate to the built environment and the construction industry are discussed. The specific policies below derive from the general policies cited previously.

2.2.7.2.2.1 Waste and recycling / Waste Framework Directive

This part of EU waste policy has the objectives of limiting waste generation and landfilling, increasing recycling rates, and extracting high-quality resources from existing and future waste. The Waste Framework Directive is the main policy document that sets out fundamental principles for waste management in the EU, emphasizing that waste should be managed in ways that protect human health and the environment. It introduces the "polluter pays principle" and "extended producer responsibility" to ensure that those responsible for waste bear the costs of its management and therefore encourage circular solutions. The Directive outlines the five-step "waste hierarchy," prioritizing waste prevention and recycling over disposal. [278]

Figure 31. Waste hierarchy aimed at by the waste law to achieve desired management principles [278]

Key targets include increasing recycling rates for household and construction waste by 2020, 2025, and beyond. In this framework, criteria are set for when waste can be classified as a by-product or ceases to be waste through the end-of-waste concept.

It is important to note that in the proposal for a targeted revision of the waste framework directive in 2023, the keywords “building”, “concrete”, and “construction” are not addressed in reference to the industry, and the focus is rather on the textile industry.

In a report published by the Institute for Prospective Technological Studies [279] one of three case studies related to the end-of-waste methodologies discusses construction aggregates and it reveals a relevant insight in the conclusion on secondary aggregates from industrial by-processes, stating that the primary goal is always the main product and that the raw materials and production process(es) cannot change to adapt for the by-product qualities at the cost of the primary product, therefore, the imposition of end of waste condition is not feasible in every case. Relating back to project CO2RDRES, the secondary materials that are by-products of concrete aggregates production processes follow the same logic, and their heterogeneity poses a challenge to their regular reuse or an end-of-waste status concept that isn’t tailored specifically to each by-product.

Another target according to the same study is to be able to identify and remove all hazardous substances and the nonhazardous ones that can jeopardize recycling or reuse of building elements or demolition products / aggregates through depolluting and selective demolition practices. However, this is still not part of the EU directive.

2.2.7.2.2.2 Critical raw materials

As the EC considers certain lists of materials essential to the continental economy and the backbone of many industries and technologies, it established the critical raw materials act (Regulation EU 2024/1252) [280] which aims at securing sustainable and reliable supply sources of such materials, most of which come from outside of the EU.

The connection of this policy to the built environment is that although the construction industry's raw materials such as aggregates, limestone, wood, and iron, are not in the lists that are published and updated by the EC, they are part of the study as non-critical raw materials and integrate the material system analysis (iron and aggregates). The system aims to track the flow of raw materials throughout the entire lifecycle steps from its entry into the system, through its use and eventual exit through end-of-life or recycling, reuse, etc. Through this information, a clearer picture can be drawn on the end-of-life recycling rates, imports and exports of materials, materials that are in stock or in use, and the extent to which recycled materials meet the demand for secondary raw materials in manufacturing through the end-of-life recycling input rate. [281]

A study published by the EC on the non-critical materials part [282], details fact sheets on construction industry related raw materials such as aggregates, iron ore, kaolin, limestone, wood, and silica sand including overviews on the value chain of each one of those materials, a market analysis with a supply and demand forecast, production, uses, origins, and further considerations on environmental and socio-economic issues wherever it is the case. This report signals that the EU is keeping an eye on those materials and their supply chain in case they become to be considered as critical in the future due to market shifts, supply shortages or any other reason hinting that they are important materials for future policy considerations. The last update of the critical materials list happened in 2020 as the fourth revision listed 30 materials, up from 27 in 2017 and 20 in 2014, ultimately doubling from the 14 materials listed in the first version in 2011 nine years earlier. Given the trend, the next revision could see new materials added to the list of critical materials in the EU.

2.2.7.2.2.3 Sustainable products and eco-design

The Eco-design for Sustainable Products Regulation EU 2024/1781 was elaborated by the EC as a part of the package aiming to achieve the objectives of the EU's 2020 Circular Economy action Plan, establishing a framework for the setting of eco-design requirements for sustainable products (concrete rules to be adopted progressively), amending EU Directive 2020/1828 and EU Regulation 2023/1542 [283], [284]. It comes after a public consultation process of the Sustainable Products Initiative that started in 2020.

The EC states through this regulation its intention to create an Eco-design Forum with diverse experts to consult on eco-design standards that can help develop and evaluate new requirements and where self-regulation measures from industry are encouraged so that stakeholders can propose their own measures for products not covered by the current law. This step also allows for flexibility in adapting to the future scenarios that might take place.

Regarding the construction sector, the law states that cement and construction products fall under both the Construction Products Regulation and this new regulation as well with the former giving prevalence over the latter for energy-related products that are also construction products. However, new delegated acts setting eco-design requirements for cement should be adopted between December 2028 earliest and January 2030 latest.

The new measures introduced by this regulation include:

(a) Digital Product Passport

The Digital Product Passport (DPP) is a digital identity card for products, components, and materials that stores essential information to enhance product sustainability, promote circularity, and ensure legal compliance. Accessible electronically, the DPP can assist stakeholders such as consumers, manufacturers, and authorities in making better decisions regarding sustainability and regulatory adherence. The regulation foresees that the EC will determine the information to be included in the passport in consultation with stakeholders, depending on the product type. This information may cover the product's technical performance, materials and their sources, repair possibilities and history, recycling options, and environmental impacts throughout its lifecycle. [283]

(b) Increased transparency and performance

This regulation sets the requirements for information, performance, and eco-design requirements. Article 4 describes the information requirements that are set to be included in the DPP, as well as complementary information on product performance, including repairability, durability, carbon or environmental footprint, guidelines on maintenance, repairs, and end-of-life handling, guidance for treatment facilities on disassembly, reuse, recycling, or disposal. There is also a provision for disclosure of any substances that are of concern.

As for performance, products are expected to meet the requirements in single specified delegated acts that are adopted together with this regulation and that are naturally different for each sector / product.[284]

(c) Eco-design requirements

- Product Aspects: to improve products aspects such as durability, reliability, reusability, upgradability, repairability and maintenance, refurbishment, and energy, water, and resource efficiency, recycled content, remanufacturing, recyclability, material recovery, and overall environmental impacts, including carbon footprint and waste generation.
- Preventing Obsolescence: to ensure products do not become obsolete due to poor design, lack of robust components, difficulty in disassembly, unavailability of repair parts, or incompatible software updates.

The EC will further develop tools and methodologies as needed to set these requirements in line with EU priorities and laws, consider international agreements, and evaluating the impact on the environment, human health, and market conditions.

However, the regulation states that requirements should not negatively impact product functionality, health and safety, consumer affordability, competitiveness, or impose unnecessary burdens. This suggests that for the text works towards prioritizing efficient economic solutions and that additional support for a transition that might require extra investments or might produce burdens is not foreseen.[284]

(d) The end-of-life of unsold products

Although this does not affect the construction industry specifically, there are products that have validity dates such as cements and chemical admixtures, that might come to bring more transparency on business models and the quantity of products that are discarded by companies.[284]

(e) Green public procurement

Article 65 of this regulation introduces mandatory Green Public procurement criteria that stipulate that contracting authorities must award public contracts that comply with specific environmental requirements for products and services covered by relevant delegated acts, by setting requirements through implementing acts, which may include technical specifications, award criteria, or contract performance conditions. The requirements focus on selecting top-performing environmentally sustainable products, with significant weight given to environmental criteria (15%-30%) in the tendering process. Furthermore, at least 50% of procurement activities should involve the most sustainable products. Not much is explicitly mentioned on circularity or methods and tools for decision making, neither on social aspects, but given the context of the regulation text, it could push towards more circular procurement practices.[284]

2.2.7.2.2.4 Level(s) - The European framework for sustainable buildings

This framework provides a common language to assess building performance and supports improvements from design to end-of-life for residential and office buildings. It was developed by the European Commission to enhance sustainability and circularity in the built environment. It establishes a standardized methodology for evaluating and reporting a building's sustainability performance throughout its lifecycle. The framework applies to both residential and office buildings, and offers three levels of assessment complexity. It is centered around six key sustainability objectives: reducing greenhouse gas emissions, promoting resource-efficient material lifecycles, ensuring efficient water use, creating healthy indoor environments, enhancing climate resilience, and optimizing lifecycle costs. Aimed at construction professionals, investors, policymakers, and other stakeholders, Level(s) aligns with EU sustainability policies, including the European Green Deal, and integrates with existing certification schemes. As an open-source tool, it is freely accessible and undergoes improvements based on user feedback [277].

2.2.7.2.2.5 The Strategy for a Sustainable Built Environment

Initially announced in 2020 as part of the Circular Economy Action Plan related to the built environment, this strategy has not been launched as of early 2025 [276]. Initially expected to launch in 2021 it aimed to enhance material efficiency, minimize climate impacts across a building's lifecycle, and integrate CE principles into construction. Proposed measures included revising the Construction Product Regulation, setting recycled content requirements, promoting digital logbooks for buildings, and incorporating lifecycle assessments into public procurement.

Its links to other strategies such as the EU biodiversity strategy with promoting soil related initiatives and the promises of a revision of other laws such as the waste law puts it at an important holistic level of functioning beyond just building materials. Another point that can relate to project CO2REDRES is the confirmation of the Commission that it would include a revision of the Construction Product Regulation to enhance the sustainability of construction materials, potentially by setting recycled content requirements for specific products.

Beyond the European policy, the further national circular policy of Luxembourg, which is largely based on the European policy landscape, is not discussed in this chapter but rather as a research outcome in the results section of project CO2REDSAP, based on a mix of literature and interview content input so that the analysis is more complete and in physical proximity in the text.

Part II | Research methodology and data analysis of project CO2REDRES

This page intentionally left blank

3 Methodology CO2REDRES

Project CO2REDRES is part of an *Interreg Grande Région* project with other universities as mentioned in section 1.1. This section describes in detail the methodology followed for action no.4 of this project that was carried out at the University of Luxembourg and is part of this thesis.

3.1 Project CO2REDRES

The research concerning the University of Luxembourg was related to the task of studying the properties of the waste materials to assess the feasibility of their use and further employment as SCM additions by the industrial project partners. The concept essentially consisted of replacing part of the cement with powders obtained from the treatment of these waste materials, rich in clay minerals which are beneficial to the cement paste matrix due to the reasons explained in the literature review section. These materials are essentially the remains or sub products of gravel washing in mines and are normally deposited in nature in form of a mud or sludge.

By valorizing GWM, this project not only contributed to the sustainability of cement, but also reduced the impact of gravel mines and other mining activities on the environment. The GWM in form of a wet sludge was collected from the partners, then dried and ground into fine powders, and heated to a temperature of up to 850°C - about half that of the ordinary Portland cement manufacturing process where temperatures in the kiln reach up to 1400°C. After studying the physical and chemical properties of the powders, they were incorporated into mixtures with cement to form pastes and mortars whose compressive strength was then determined. The pozzolanicity potential of these SCM, as well as the mechanical resistance of the pastes and mortars containing them have been completely studied and the methodology followed will be detailed in this section of the thesis.

3.2 Explanation of research design.

The main objective of this study was to assess the feasibility of using different GWM as SCM to partially substitute cement in OPC concretes. To create a better view on the physical properties and chemical and mineralogical composition of the studied GWMs and to help assess their pozzolanic potential, an experimental procedure consisting of testing the properties of the GWM powders before and after thermal and mechanical activation was designed. The performed characterization tests are discussed in length in this section as well as the preparation and testing of paste and mortar specimens containing these GWMs.

The research was planned over a period of two years and consisted of studying the best way to treat the raw materials initially chosen with the project partners through knowing an array of properties that are essential in this type of SCM.

Table 10. Names and origins of the GWM powders used.

Sample ID	Origin	Type
S1	Germany	Gravel wash mud from mining
S2	Germany	Gravel wash mud from mining
S3	Germany	Gravel wash mud from mining
S4	Belgium	Gravel wash mud from mining
S5	France	Gravel wash mud from mining
S6	Luxembourg	Gravel wash mud from mining
S7	Germany	Overburden clay material layer from mining

The first step was to characterize the materials through different tests prior to and after activation to be able to compare the results. As certain basic properties of the materials chosen for this phase were known, it was easier to determine the type of treatment needed. In the initial project steps other treatment methods such as chemical activation were considered as well but ended up not suiting the chosen materials due to their chemical and mineralogical compositions. For this reason, the chosen treatments were calcination and milling, i.e., thermal, and mechanical respectively, also given the capacity of production plants and project partners. The idea of the project was to supply the industrial partners with concepts that could be useful for their current capacities. The full material treatment process is shown in the flowchart of Figure 32.

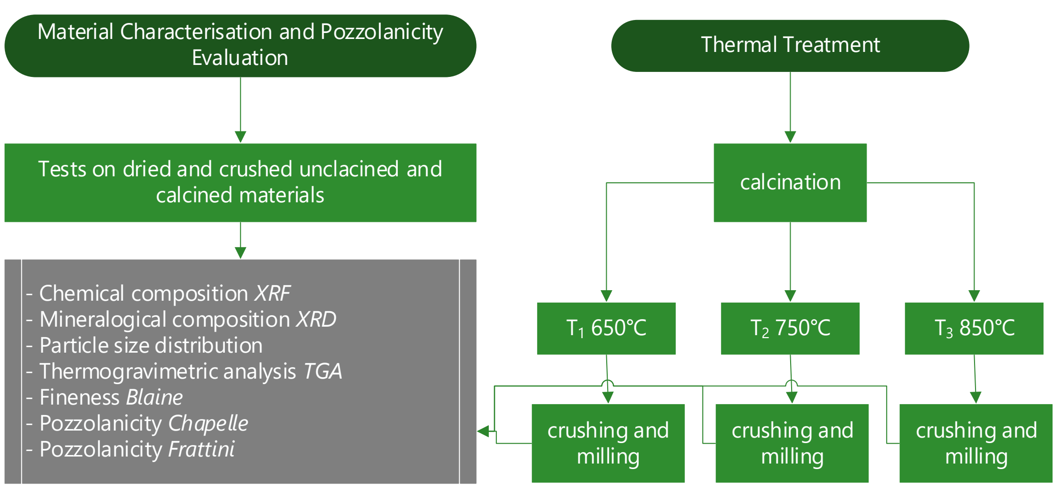


Figure 32. Material treatment process flowchart including characterization tests performed.

3.3 Description of experiments, data collection methods and instruments.

This section describes the different steps of the experimental methodology followed for project CO2REDRES and is divided into three parts: material preparation, characterization tests, and activation procedures.

3.3.1 Material preparation

The studied samples of GWM (S1 to S7) were all received from the respective research partners saturated with varying water content from 10 to 45%. The water content for each sample was measured after drying for 24 hours at 105°C until achieving constant weight ensuring full evaporation. Posteriorly, the dried samples were ground into a fine powder by using a jaw crusher and a then rotating mill with a 2mm meshed sieve afterwards, this powder was then used for calcination. Prior to calcination, both the jaw crusher and the rotating mill were used for one cycle only with the same opening and a sieve with a 2mm mesh for all material samples. Subsequently, the powders were crushed and grinded once more after calcination to ensure that any particle agglomeration as a possible result of the calcination process is excluded. The thermal treatment (calcination process) was used as a method of improving the reactivity of the aluminosilicates present in the clay portions of the gravel wash muds through dehydroxylation of the clay whereby an amorphous phase is formed [25], [285]. Dehydroxilation allows the formation of an amorphous phase where silicon and aluminum from the clay become chemically reactive with the CH formed during the hydration reaction of cement creating compounds with cementitious properties.

However, the optimal temperature for each GWM sample is unique and is affected by the type of clay minerals present [110], [119], [285], the crystallinity and the particle size distribution of that sample [23]. Nevertheless, the optimal range has an upper limit beyond which sintering, a phenomenon of particle agglomeration and recrystallization, forms inactive phases, and below which complete dehydroxilation might not fully occur [286].

The calcination procedure followed for all materials started with the heating of the ground powders in layers of 1.5 cm in ceramic bowls starting at room temperature with a heating rate of 5 °C/min to reach the target temperature of 750 °C, 850 °C or 950 °C, where the temperature was maintained for 2 hours and then passively cooled down in the furnace chamber back to room temperature. The oven used was a chamber furnace with radiation heating (Model ASM 30, Shroeder Industrieofen GmbH, Germany). The weight loss on ignition was then measured and recorded. The material preparation cycle together with the activation processes chosen were the same for all studied samples and are summarized in the flowchart in Figure 33. The detailed calcination and grinding procedures are discussed in section 3.3.3

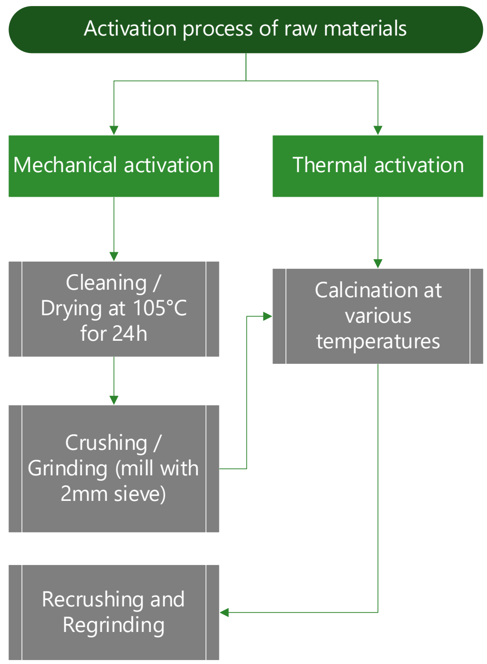


Figure 33: The material preparation flowhcart.

3.3.2 Characterization tests

To understand the physical and chemical characteristics of the materials that were used pre and post calcination, a full set of tests was carried out since various parameters of cement are vital to determine the final properties of concrete, and it could not be any different with the SCMs that are used in the binder matrix. Each one of the tests is detailed further in this section.

3.3.2.1 Physical properties characterization

3.3.2.1.1 Particle size distribution PSD

When mixing SCM powders with cement, their particle size influences that of the final mixture, and since the modification of physical properties is one of the most sustainable methods for enhancing the cement performance [287] it is important to have this parameter well determined.

The PSD was obtained with laser granulometry analysis that measures the diffraction of laser beams in the sample powder to determine the particle sizes in this sample. Laser diffraction measures particle size distributions by observing the angular changes in light intensity as a laser beam passes through a sample of dispersed particles. Larger particles scatter light at smaller angles relative to the laser beam, while smaller particles scatter light at larger angles. The angular scattering intensity data is then analyzed to determine the size of the particles that produce the scattering pattern. By combining the patterns, a scatter is formed and then a percentage of the amount that scatters at each angle is calculated and sums up to 100% giving a graphic distribution that shows the percentage of particles of each size in the sample.

3.3.2.1.2 Particle fineness – Blaine

The Blaine fineness was measured using the Blaine Air Permeability Apparatus which consists of simply measuring the resistivity of airflow through a porous bed of a dry powder, usually cement, to determine its surface area. Since the materials used were fine clays whose structure resembled that of cement the same apparatus could be used without any additional adaptations, also given the fact that the SCM were used as cement substitutions, and it would be reasonable to compare their properties to those of cement. Figure 4. The general dry process of cement manufacturing adapted [49].Figure 34 shows the schematic drawing of the components of the components of the testing system. Although automated machine tests are available, the method used in this study was the manual one.

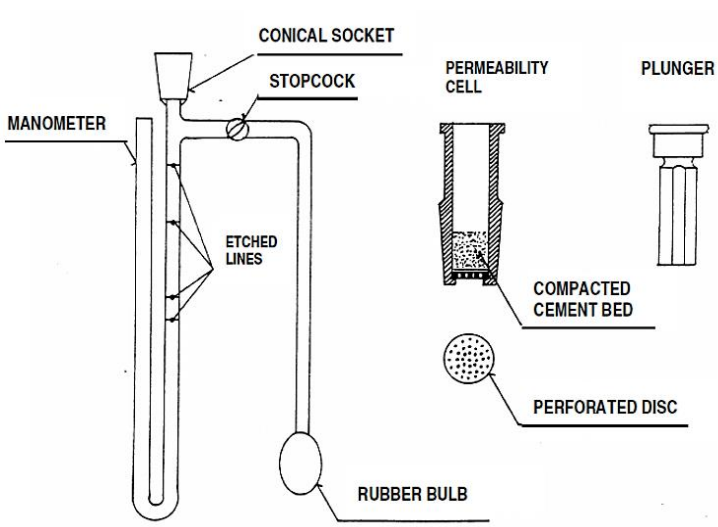


Figure 34: Blaine air permeability apparatus sketch [288].

To start the measurements, certain parameters were measured and calculated to obtain the bed height and the volume of the permeability cell to fill. The height and diameter of the permeability cell, and the plunger length were measured with a digital ruler to calculate the necessary bed height and volume of the sample to be tested. The average values of 6 measurements are shown in Table 11.

Table 11. Blaine apparatus measurements for initial test values.

Sample	*m1*	*ρ*	*T* (20 ± 2)	*J* (cell height)	*F* (plunger length)	G (cell diameter)	H (bed height)	r	V
[-]	[0.5 x ρ x V]	[g/cm3]	[°C]	[mm]	[mm]	[mm]	[J-F] mm	[mm]	[H x r2 x 3.14 /1000] cm3
T1	-	-	-	51	35	12.7	-	-	-
T2	-	-	-	51	35	12.7	-	-	-
T3	-	-	-	51	35	12.7	-	-	-
T4	-	-	-	51	35	12.7	-	-	-
T5	-	-	-	51	35	12.7	-	-	-
Averages	-	-	-	51	35	12.7	16	6.35	2.03

Once the density of each powder was calculated, and the volume needed in the cell was known, the needed mass of the sample could be calculated in grams by the equation m = 0.5 x ρ x V.

The detailed step procedure was followed according to EN 196-6:2018 [288].

1. The temperature of the room was measured at the beginning of each set of readings and recorded to match the requirement of 20 ± 2 °C.
2. A thin layer of wax was applied to the cell.
3. A filter paper disc was then placed at the bottom in contact with the metal perforated disc and then followed by the premeasured amount of powder. After tapping the powder slightly to level, another paper disc was placed on top and compacted with the plunger.
4. Once compressed, the plunger was removed, and the permeability cell attached to the manometer tube through the conical socket slowly allowing the air to evacuate the apparatus until the liquid reaches the top-level mark.

5. Once the liquid had reached that middle mark the timer was started and then stopped once the third mark had been reached. This is the recorded time used in the formula to calculate the surface area:

   $S = (52.43 \times K \times \sqrt{t}) / \rho$, where:

   K is the apparatus constant = 2.7

   t is the time elapsed described in step 5 [s]

   ρ is the measured density of the tested powder [g/cm^3]

This test was performed for the calcined grinded powders at 750°C, and the uncalcined grounded powders for each of the studied materials for the portion finer than 90µm.

3.3.2.1.3 Density

The density of each of the calcined powders was measured using glass pycnometers in a temperature-controlled environment at 23°C. Pycnometers are flasks of a predefined volume where the sample can be weighed with and without a fluid of known density. Then the density of the substance is calculated as the ratio of the difference of the two weights to the known flask volume. The followed procedure can be consulted in the second row of Table 12.

Table 12: Calculation parameters for density measurements.

Sample Name	w_1	w_2	w_3	w_4	ρ	δ	δ av
	glass + petrol	*glass + 1/2 petrol*	*glass + 1/2 petrol + SCM material*	*glass + material + petrol refilled*	Density of petrol	Density of material	Average for three measurements
[-]	[g]	[g]	[g]	[g]	[g/cm^3]	[g/cm^3]	[g/cm^3]
					0.79	$(w_3 - w_2)/(w_3 - w_2) + w_1 - w_4$	

The measuring of the density was essential for the Blaine measurement and as a confirmation of homogeneity of the samples to support the substitution by weight of PC in the studied paste and mortar samples.

3.3.2.1.4 X-ray Diffraction (XRD)

The mineralogical composition can be studied by x-ray diffraction (XRD) methods using spectrometers. The XRD characterization was studied with a D8 Endeavor X-ray diffractometer (from Bruker AXS). The experiment was carried out of the University's lab by a partner researcher.

The procedure entails grinding a fine powder sample and placing it in a disc (often mixed with wax depending on the machine used) then bombarding it with x-rays. X-rays are generated using an X-ray tube, which typically consists of a cathode and an anode. When high-voltage electricity is applied, electrons are accelerated and collide with the anode material (usually made of copper), producing X-rays. The theory behind the measurement is how the X-rays interact with the sample's particles as they get diffracted by the crystal lattice planes within the material. This diffraction is dependent on the wavelength of the x-ray, the distance between the crystals, and the angle of incidence. Once these rays have been diffracted, they are registered by a detector which measures the intensity of the diffracted x-rays at the different angles at which they are positioned. The detector collects data on the intensity of the diffracted X-rays as a function of the diffraction angle, creating a diffraction pattern. This pattern consists of peaks corresponding to the angles at which the X-rays are constructively interfered by the crystal planes. This test was carried out of the university labs with an academic project partner.

3.3.2.1.5 X-ray Fluorescence (XRF)

The chemical composition of a sample material can be determined X-ray fluorescence (XRF) which is a non-destructive analytical technique that works by exposing a prepared sample to an X-ray beam from an X-ray tube or a radioactive source which causes the excitement of the electrons in the sample. The energy from the beam ejects inner-shell electrons from the atoms in the sample. When an inner-shell electron is ejected, an electron from a higher energy level (outer shell) falls into the empty lower-energy level to fill the void. This transition releases energy in the form of secondary (or fluorescent) X-rays, characteristic of the specific that specific element. The emitted X-ray fluorescence is then detected and measured by an energy-dispersive or wavelength-dispersive detector. Each element emits X-rays at unique energies, so the detector can identify and quantify the elements present in the sample.

The powder samples were prepared in form of a pellet, then placed in the machine for the testing. A spectrum of the peaks corresponding to different elements were then generated, and the composition in percent identified by the software. This test was carried out of the university labs with an industry project partner.

3.3.2.1.6 Thermogravimetric analysis

The thermogravimetric analysis (TGA) for untreated materials was also carried out to obtain the pattern of heat flow and weight loss under elevated temperatures from 50°C to 1000°C and supply an image to the behavior of the natural materials under the influence of heating. Therefore, the detection of the optimal temperature where the dehydroxilation of clay minerals happens is expected to support the results of the compression strength tests for each different calcination temperature addition. The TGA analysis was carried out with an STA 449 F5 Jupiter thermal analyzer at air atmosphere and with a heating rate of 20 °C/min.

3.3.2.2 Pozzolanicity potential evaluation

Although the physical and chemical properties of the materials offer an idea on their pozzolanic activity potential as discussed in section 2.1.2.5, the specific tests that are exclusively related to pozzolanic activity are describes in this part.

3.3.2.2.1 Direct pozzolanicity – Chapelle test

The modified Chapelle test methodology was used as described in the literature under section 2.1.2.5, following the detailed procedure below:

(a) *Sample Preparation*: Weighed 1 gram of the tested sample material and mixed with 2 grams of lime / calcium oxide, then added 250 mL of deionized water in a clean Erlenmeyer flask stirring the mixture thoroughly to ensure it is well-dispersed.
To prepare the CaO, pure $CaCO_3$ was calcined at 1000°C for 30 minutes and loss on ignition (LOI) measured at 44%.

(b) Heating phase: Placed the flask on a heated stirrer with a Teflon magnet set at 90°C for a period of 16 hours keeping the temperature constant and the stirring continuous to prevent settling. The setting was controlled with an automatic electrical switch and a refrigerated column fitted with a thermometer to keep the solution from evaporating (*Figure 35*).

Figure 35. Chapelle test setup in the laboratory.

(c) *Cooling phase*: After 16 hours, the flask was removed from the experimental setup and the mixture allowed to cool to room temperature.

(d) *Filtration:* A fresh saccharose solution (250ml distilled water + 60g of saccharose) was prepared and then mixed into the pozzolan-lime system for 30 minutes on a magnetic stirrer. Then, the mixture was filtered using filter paper to separate the solid and liquid components and the filtrate was collected in another container.

(e) *Titration:* 25 mL of the filtrate for titration were pipetted out and titrated with a 1 N hydrochloric acid (HCl) using phenolphthalein as a pH indicator until the neutral point has been reached. The volume of HCl used to reach the endpoint was then recorded for three titrations.

(f) *Results:* The amount of calcium hydroxide consumed by the pozzolanic material was calculated using the titration data as shown in Table 13, where:

- V1 is the volume of HCl necessary for the titration of 25 ml of solution obtained by the blank sample without any tested pozzolan material (control).

- V2 is the volume of HCl necessary for the titration of 25 ml of solution obtained by the reaction with the pozzolan sample.

The titration reaction is:

$CaO + 2HCl \rightarrow CaCl_2 + H2O$

$Ca(OH)_2 + 2\ HCl \rightarrow CaCl_2 + H2O$

- Check of the blank reaction: $(56/2) \times V1 < 1000$

-Results are expressed in mg of $Ca(OH)_2$ fixed per gram of tested clay/pozzolan

Table 13. Chapelle test data calculation structure.

Sample	V_1 [mm of HCl 0.1]	V_2 [ml of HCl 0.1]	$Ca(OH)_2$ [mg fixed per g of pozzolan]	Control sample check
Weight [g]	A	B	C	D < 1000
1g	blank sample	pozzolan sample	$C_i=2x((A_i-B_i)/Ai)x74/56x1000$	1000

3.3.2.2.2 Direct pozzolanicity – Frattini test

Frattini test was carried out in accordance to EN 197-5 [95]. As mentioned in the literature section this method assesses the pozzolanicity by comparing the concentration of calcium ion (calcium oxide) present in the solution in contact with the sample of hydrated cement-pozzolan system, after a fixed period of 8 or 15 days, with the quantity of calcium ion capable of saturating a solution of the same alkalinity. The sample material is considered to be pozzolanic if the concentration of calcium ion in the solution is lower than the saturation concentration.

(a) Sample preparation

For the sample preparation 20g of sample (80% OPC and 20% tested pozzolan) was weighed and mixed with 100ml of previously boiled water brought to a uniform temperature of 40°C in a hermetically sealed plastic container. The container was then shook for 20s to avoid lumps and then placed back into the temperature enclosure for the period needed.

(b) Standardization of the EDTA solution

For the standardization of the titrating solutions, first the Ethylenediaminetetraacetic acid (EDTA) solution was prepared and the factor f1 calculated. In a glass beaker with approximately 100 ml of water, 10 ml of hydrochloric acid (1 + 2) i.e., prepared by adding 250 ml of concentrated hydrochloric acid to 500 ml water, was added, and brought to boil to release the dissolved CO_2 then cooled down to room temperature. The solution was then transferred to a volumetric flask with added water to attain 1000 ml. Subsequently, the pH of 50 ml of the calcium solution was adjusted to (12,5 ± 0,2) with a sodium hydroxide solution and the endpoint determined using Patton and Reeders reagent titrating with a 0,03 mol/l EDTA solution until the color changed from purple to clear blue. The volume V_1 (see

Table 14) is then used to calculate the standardization factor f_1 using the formula below, where:

$$f_1 = \frac{m_1}{V_1} . 16,652$$

m_1 is the mass of calcium carbonate, in grams.

V_1 is the volume of EDTA solution used for the titration, in milliliters.

(c) *Standardization of the 0,1 mol/l solution of hydrochloric acid*

A quantity of 0,2g of sodium carbonate was weighed to an accuracy of ± 0,000 5 g, then dissolved in 50 ml of water in a conical flask. The solution was then titrated with the 0,1 mol/l dilute hydrochloric acid using methyl orange as an indicator. The endpoint is the color change from yellow to orange, and the volume V_2 (see

Table 14) used to determine the factor f_2.

$$f_2 = \frac{m_2}{V_2} . 188,70$$

m_2 is the mass of sodium carbonate, in grams.

V_2 is the volume of hydrochloric acid used for the titration, in milliliters.

Table 14. Calculation of standardization factors for EDTA and HCl solutions used in Frattini test.

Sample			*8.1 EDTA Standardization*			*8.2 HCl 0.1 mol standardization*		
Name	Weight SCM [g]	Weight OPC [g]	$CaCO_3$ m_1 [g]	V_1 [ml]	f_1 [-]	$NaCO_3$ m_2 [g]	V_2 [ml]	f_2 [-]
Standardization EDTA 1			1.00	10.40				
Standardization EDTA 2			1.00	9.50				
Standardization EDTA 3			1.00	10.45				
Standardization EDTA 4			1.00	9.90				
Av. Standardization EDTA			1.00	10.06	1.65			
Standardization HCl 1						0.20	36.80	
Standardization HCl 2						0.20	37.10	
Standardization HCl 3						0.20	36.90	
Av. Standardization HCl						0.20	36.93	1.02

(d) *Determination of the hydroxyl ion concentration*

The tested samples were retrieved from the climatic chamber at 8 days and the solution quickly filtered under vacuum through a Buchner funnel into a vacuum flask using dry double filter paper, the sealed and let cool to room temperature.

Subsequently 50ml of the solution were used to determine the total alkalinity with the 0.1 mol/l dilute hydrochloric acid. The indicator used was the methyl orange and the titration endpoint corresponded to the color change from yellow to orange.

The hydroxyl ion concentration, $[OH]^-$, was then calculated using the formula:

$$[OH]^- = 2\,.V_3.f_2$$

Where,

V_3 is the volume of 0,1 mol/l hydrochloric acid solution used for the titration, in milliliters.

f_2 is the factor of 0,1 mol/l hydrochloric acid solution calculated in (c).

(e) *Determination of the calcium oxide concentration*

With the same titrated solution as in (d), the pH was adjusted to 12.5 with the sodium hydroxide solution and titrated with the 0.03 mol/l EDTA solution determining the endpoint by using Patton and Reeders reagent.

The calcium oxide concentration, [CaO], was then calculated using the formula:

$$[CaO] = 0{,}6\,.V_4.f_1$$

Where,

V_4 is the volume of EDTA solution used for the titration, in milliliters.

f_2 is the factor of the EDTA solution calculated in (b).

(f) *Assessment of pozzolanicity through the graph plot*

The concentrations calculated for both hydroxyl and calcium ion were plotted on the graph presented in section 2.1.2.5, Figure 9. Each studied material was tested for the three calcination temperatures and for each test the mean value of three measurements taken. All materials were tested at 8 and 15 days.

3.3.2.2.3 *Indirect pozzolanicity – Strength Activity Index (SAI)*

This indirect method for the evaluation of pozzolanicity is used to measure the mechanical strength of the hardened binder and mortar specimens at different curing times and consists of calculating an index in percentual points as compared to the absolute value of the reference strength. Three specimens of each mixture were prepared for each curing date and the compressive strength was measured on each of the six halves obtained after the bending test, using a compression strength testing machine of 300kN nominal capacity.

The specimens were controlled after the curing period, measured, and weighed before the test to ensure uniformity [106]. According to the European Standard EN 196-1 [13], a material is said to be pozzolanic if the mortar in which it substitutes OPC yields a compressive strength of at least 75% that of the reference at 28 days and 85% at 90 days. The full preparation procedure and curing conditions are described in section 3.4

In total more than 500 compression tests were run.

3.3.3 Activation procedures

As discussed in the literature section, raw clays in general present low pozzolanic activity. To increase their reactivity, materials containing clays must be activated prior to blending with cement. Activation involves dehydroxylation and amorphization of clay minerals, altering the structure and coordination of their ions. These processes increase the solubility and reactivity of aluminum and silicon ions, which is essential for clay minerals to present pozzolanic activity. The activation process of clays can be achieved mechanically through grinding or thermally by heating (see Figure 32 in this section and Table 6 in section 2.1.3.4.2. The thermal method involves heating the clay to a temperature that is high enough to break down the clay mineral structure but not so high that it causes recrystallization and the formation of chemically inert phases [119].

The choice of the temperature ranges for thermal activation was decided based on the chemical / mineralogical content of the samples, being all rich in clay content with varying quantities of kaolinite and illite, thus needing a range from 600 to 900°C [289] for complete calcination. Since the materials were not pure homogeneous clays it was impossible to predict the optimal temperature beforehand, so 650, 750 and 850°C were chosen based on the clay content combination having different clays with different dehydroxylation temperature ranges and previous studies related to clay [119] and GWM properties [25] .

Two different ovens were used, one for drying and another for calcination. The samples were dried for 24 hours at a constant temperature of 105°C and monitored until all the external water content has evaporated and a constant weight was reached, before the mechanical activation. The first mechanical activation was carried out with the dried samples that were ground into a fine powder by using a jaw crusher (Model DR80, Dietz-mtoren KG, Germany) to form a powder from the dried chunks and a then properly grinding this powder through a 3 blade rotating mill (Model SK1, Retsch GmbH, Germany) with a 2mm meshed sieve insert, this powder was then used for calcination. Both the jaw crusher and the rotating mill were used for one cycle only using the same opening and the same sieve respectively, therefore grinding time is not a considerable variable in this study.

Therefore, the powders were ready for thermal treatment. The calcination procedure followed for all materials started with the heating of the ground powders in layers of 1.5 cm in ceramic bowls starting at room temperature with a heating rate of 5 °C/min to reach the established target temperatures of either 750 °C, 850 °C or 950 °C where the temperature was maintained for 1 hour and then passively cooled down in the furnace chamber back to room temperature (in 24 hours). The oven used was a chamber furnace with radiation heating (Model ASM 30, Shroeder Industrieofen GmbH, Germany).

Following the calcination, the powders were then grinded again using the same initial procedure described previously.

3.4 Design of investigated mixes

This section describes the design of the investigated mixes for pastes and mortars containing SCM.

3.4.1 Cement- calcined GWM binder paste mixes

The paste mixtures containing OPC and calcined GWM that were prepared for the seven different samples had the same composition proportions as described in Table 15. Twenty-one different OPC-GWM binder mixes were designed to integrate the calcined GWM powders at the three calcination temperatures (650°C, 750°C and 850°C) with a fixed substitution ratio of 20 wt.%, without any additional aggregates in the mix. One reference mixture was also prepared containing only OPC. The water/binder (w/b) ratio was set to 0.4. For each mixture, three identical rectangular prisms were prepared and investigated after a curing period of 7, 28, 56 and 90 days. The mixing procedure for all the series of binder mixes consisted of briefly mixing the dry components, i.e. the

OPC and calcined GWM powder at a mixing speed of 125 rpm. Then, with the same mixing speed, the right water amount was gradually added and the contents mixed for another 180 s, afterwards the paste was mixed at 250 rpm for 90 s. The mix was then poured into a rectangular prismatic steel mold that yields three specimens of 40 × 40 × 160 mm^3 each [106]. The paste was compacted for 7 s on a vibrating table at maximum frequency. To avoid the rapid evaporation of water from the hydration reaction the cast specimens in the molds were covered by glass or polypropylene plates for 24 h until full hardening before unmolding. The specimens were then demolded, identified, wrapped in cellophane foil and cured at room temperature (+-20°C constant temperature in the underground lab installations) until 24 h before the uniaxial compression test [106]. For S2 additional specimens were prepared to examine the compressive strength for a calcination temperature of 550°C.

Table 15. Material constitution by proportion for the studied series of binders.

Mixture ID[a]				
	Substitution grade	OPC	GWM	w/b[c]
[-]	[wt. %]	[g]	[g]	[-]
REF	0	450	0	0.4
B_S1_C[b]	20	360	90	0.4
B_S2_C	20	360	90	0.4
B_S3_C	20	360	90	0.4
B_S4_C	20	360	90	0.4
B_S5_C	20	360	90	0.4
B_S6_C	20	360	90	0.4
B_S7_C	20	360	90	0.4

[a]The series name is composed as follows: B for binder, S*x* in reference to the respective GWM sample used, C for the calcination temperature, followed by the number of days of curing. Example B_S1_750_90 would identify a binder specimen with S1 as an SCM calcined at 750°C and cured for 90 days.
[b] C is the calcination temperature 650°C, 750°C and 850°C denoted in the mixture ID
[c] w/b: water to binder ratio. Binder is considered as OPC+GWM.

3.4.2 Cement- calcined GWM mortar mixes

The same procedure as in 3.4.1 was adopted, however with the gradual addition of sand aggregates after the second mixing step of the binder compound, followed by mixing at 125 rpm and 250 rpm for 90s each [106]. The mortar mixtures prepared are specified in Table 16.

Table 16. Material constitution by proportion for the studied series of mortars.

Mixture ID[a]						
	Substitution grade	OPC	GWM	CEN Sand	w/b[c]	b/ag[d]
[-]	[wt. %]	[g]	[g]	[g]	[-]	[-]
REF	0	450	0	1350	0.4	0.33
M_S1_C[b]	20	90	360	1350	0.4	0.33
M_S2_C	20	90	360	1350	0.4	0.33
M_S3_C	20	90	360	1350	0.4	0.33
M_S4_C	20	90	360	1350	0.4	0.33
M_S5_C	20	90	360	1350	0.4	0.33
M_S6_C	20	90	360	1350	0.4	0.33
M_S7_C	20	90	360	1350	0.4	0.33

[a]The series name is composed as follows: M for mortar, *Sx* in reference to the respective GWM sample used, C for the calcination temperature, followed by the number of days of curing. Example M_S1_750_90 would identify a mortar specimen with S1 as an SCM calcined at 750°C and cured for 90 days.

[b,c] Refer to the footnote of Table 15.

[d] b/ag: binder to aggregate ratio. Aggregates considered is CEN sand, matching standard EN196-1 specifications.

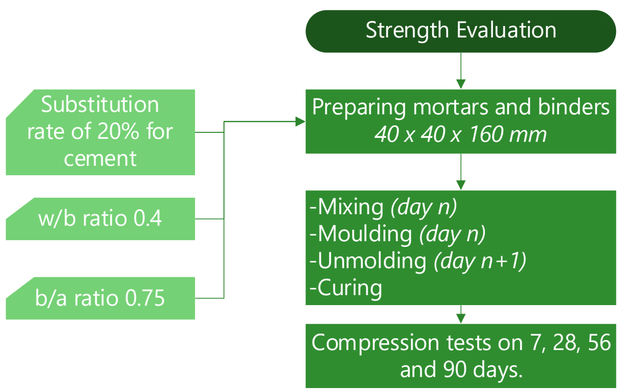


Figure 36. Strength evaluation chart for SAI.

3.5 Data collection and analysis techniques and procedures.

All the data of experimental settings were collected in the different laboratories used inside and outside of the University of Luxembourg according to the methodologies, manuals, and standards followed. The manually performed measurements were recorded on excel, and the digital computer performed measurement results saved in their respective folders then recorded on excel as well for further organization and posterior analysis. All other software used were the ones of programs linked to the machines performing tests.

3.6 Ethical considerations

Addressing ethical considerations in a laboratory-based experimental study is important to cover the basics of research and researcher integrity and responsibility. This research adheres to strict ethical standards through the following:

1. Risk management and safety

All laboratory work was conducted following comprehensive safety protocols and access was only allowed after a formal training session, a practical introduction to the lab safety codes, and passing an online test. The training included the importance and use of protection equipment, safety drills, and the adherence to emergency procedures. Risk assessments were required for experiments that could contain potential hazards, such as working with strong acids or base compounds, and using the crusher, ovens, mixers, and compression machines.

2. Environmental Impact

Efforts were made to minimize environmental harm by implementing waste reduction strategies, such as using reusable stainless-steel molds, and ensuring proper disposal of each substance depending on the internal health and safety regulations, and also using programmable timers on switches to avoid the need for use of extra electrical current when a machine is not needed.

3. Data Integrity

Data was meticulously recorded, stored securely, and reported honestly. All experimental procedures and data analyses are documented transparently to allow reproducibility, and all results are average measurements of at least three test repetitions in the same conditions.

4. Other concerns

The study did not involve human, or animal subjects and presents no potential harm in terms of social or environmental impacts, having as an only aim a constructive contribution to technological advancements in concrete / cement science.

3.7 Merits and limitations

The questions around the use of SCM are of various dominions but can mostly relate to energetic gains from substituting OPC, reducing carbon emissions, narrowing and closing the loops regarding circularity of materials, and extracting less materials from nature. All these require advances in technologies and reduction in demand for the equation to be solved [290], and this research project i.e. CO2REDRES offers part of the way forward at least conceptually by the simple yet important act of reducing clinker content in concrete and giving new life to industrial byproducts or secondary materials at the same time.

The limitations however, can be that more research might be needed on the long term to define then the performance of such materials after years of use out of laboratory controlled conditions or even incorporate them in circular construction elements to see how they fit in and how can these changes contribute to circularity of concrete in a way, because for the concept researched in CO2REDRES the circular improvements are closely related to the raw material production industry level and not to the concrete industry level.

This page intentionally left blank

4 Data Presentation and Analysis

4.1 Presentation of research findings.

With the growing emphasis on more sustainable materials and the promising research around substitution of cement with clay-based materials, many aspects of these cementitious systems are under the research spotlight. Contrasting the high global geological availability of clays, in the present only a few countries use calcined clays in cements [291], although it has been shown in a few studies, that even less pure kaolinitic clays can be used to produce reasonably reactive material [19].

This analysis will examine the characteristics of various secondary waste materials that have major clay phases, their reactivity when calcined, and their impact on the mechanical properties, and overall performance of concrete. The data presented will explore the influence of factors such as particle size, pozzolanic activity, and hydration processes, offering insights into the suitability of mixed and impure clay materials as eco-friendly cement alternatives. Through a detailed examination of these properties, this chapter aims to assess the viability of clay substitution and its implications for the construction industry's shift towards more sustainable practices.

4.2 Data analysis, including tables, figures, and charts.

4.2.1 Chemical analysis

The XRF analysis shows (Table 17) a major presence of silica, alumina and iron oxide with a varying amount. This is an important step in confirming that the samples studied contain such compounds since they are essential for the pozzolanic reaction and producing amorphous silica through calcination. The highest amount of silica among the GWM samples can be observed in S1 and S2 which equally show 73.4% of silica content followed by S5 at 71.6%. The second most abundant compound in the samples is Alumina ranging from the highest content of 23.27% in S3 and lowest of 14.8% in S1.

Table 17. Chemical composition of natural uncalcined samples in percent per compound.

	CEM	S1	S2	S3	S4	S5	S6
SiO_2	16.57	73.36	73.38	58.9	53.82	71.59	63.66
TiO_2	0.37	0.89	0.74	1.26	1.38	1.52	0.89
Al_2O_3	4.08	14.8	19.47	23.27	16.42	20.67	19.63
Fe_2O_3	3.7	6.1	3.03	11.72	7.61	1.86	9.61
MnO	0.07	0.14	0.02	0.15	0.09	0.01	0.09
MgO	1.51	0.52	0.47	0.6	5.55	0.73	1.77
CaO	69.58	0.27	0.15	0.21	6.99	0.25	0.25
Na_2O	0.29	0.15	0.16	0.13	0.77	0.13	0.19
K2O	1.21	3.21	2.37	3.2	6.64	2.8	3.5
P_2O_5	0.4	0.29	0.08	0.26	0.21	0.1	0.19

The preceding table shows the different amounts in percent of each compound present in each of the studied materials from S1 to S7 and compared to the amounts in the first column related to OPC. Another view of the same data is the below graph of Figure 37 in which the percentages are shown as a bar with the blue color indicating Silica amounts being the most dominant which confirms the initial hypothesis made for those materials: they are rich in silica, which is a good attribute for an SCM as discussed in the literature review in section 2.1.3 and throughout the chapter in general.

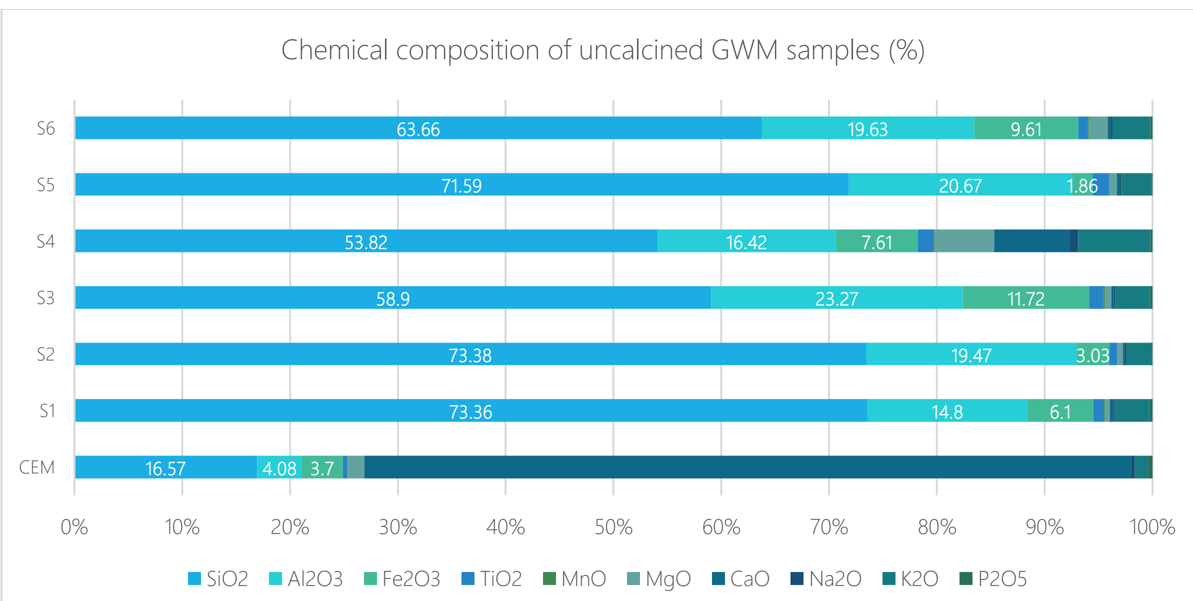


Figure 37. Chemical composition of natural uncalcined samples in percent per compound in graph format.

4.2.2 Physical properties: density, fineness, and particle size distribution

The densities of the natural samples as well as of the calcined samples (at 750°C) is shown in figure 37. The graph, having as a scale 0 g/cm^3 at its center and a value of 4 at its outermost circumference, shows an almost equidistant distribution from the center for all the samples with very slight shifts. This is an important parameter as it allows us to verify that the different materials are indeed physically similar in that aspect and that their use and comparability are valid in the experimental process further on.

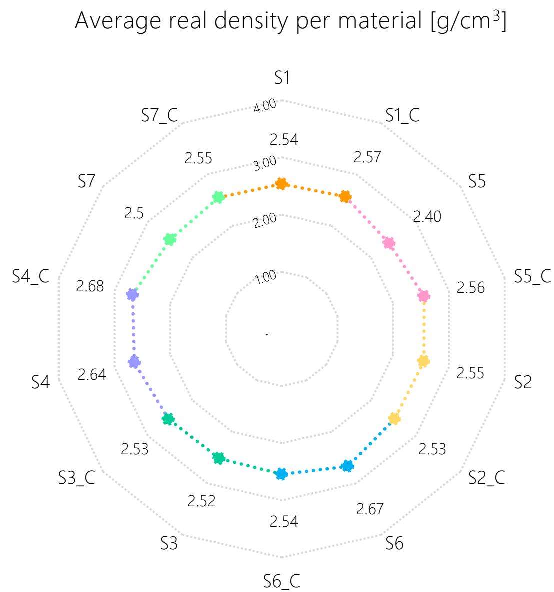


Figure 38. Average real density of each material sample. Sx refers to the natural sample and Sx_C refers to the calcined sample.

The fineness of the studied GWMs ranged from 3800 to 10700 cm^2/g as compared to 4800 of the used cement. In this range S3, S4 and S7 showed respectively the highest fineness, and the calcined samples presented a slight decrease across the various GWM samples. Although the materials used were grinded again after calcination, this effect can be traced to the sintering phenomenon that the samples undergo in the oven at high temperatures as discussed in the literature (Chapter 2, section 2.1)

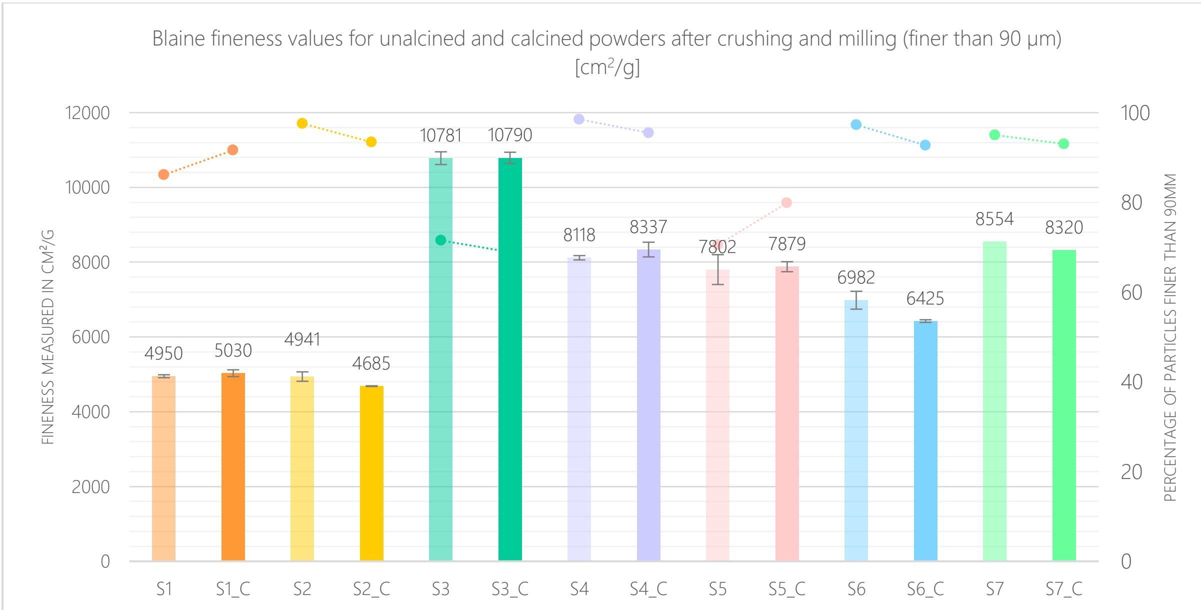


Figure 39. Blaine fineness measured for uncalcined and calcined powder samples 1 to 7.

The particle size distribution (PSD) graphs show that the materials are concentrated in around a range and they shift slightly to curves to the right-side indicating a less fine powder after calcination when compared to the natural samples. This can be explained by the fact that at such temperatures sintering is a common effect in clays. Figure 40 shows the PSD for the uncalcined samples. S7 presents the finest distribution with a d_{10} of 0.93 µm and d_{50} of 3.10 µm, followed by S3, S5 and S6, S2 and S4, and S1. The 10% and 50% passing diameters are shown in

Table 18. The finer materials show a more accentuated shift towards a coarser distribution after calcination, and this can be seen in the relation between d50 natural and d50 calcined also in

Table 18. Naturally the finest material of the sample group is S7 pre and post calcination due to its purer clayey nature.

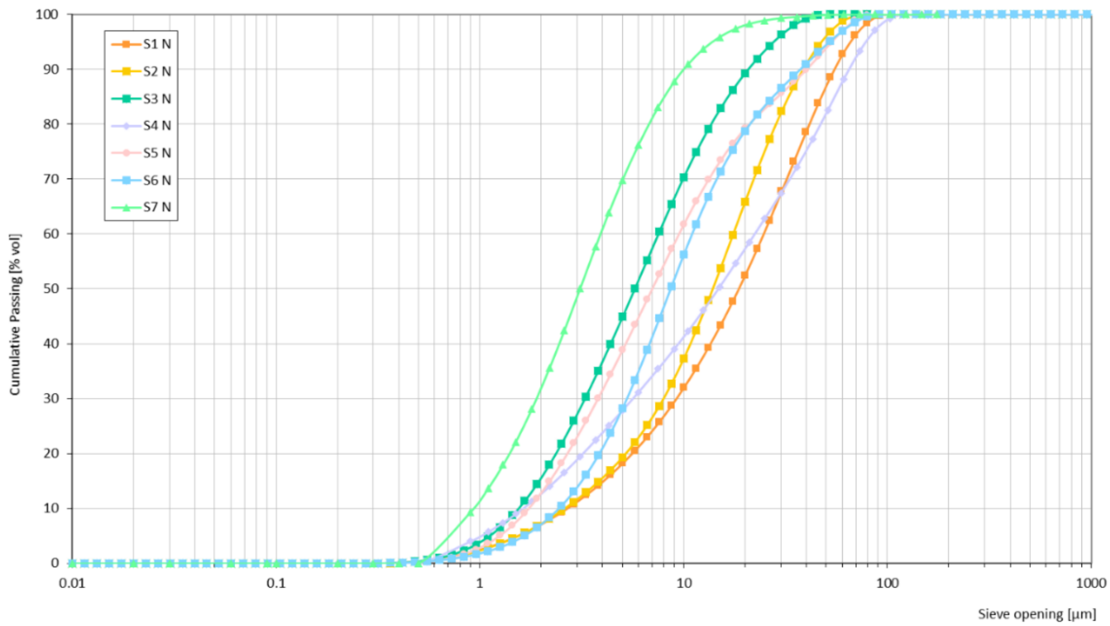


Figure 40. Particle size distribution of uncalcined sample powders finer than 125 µm.

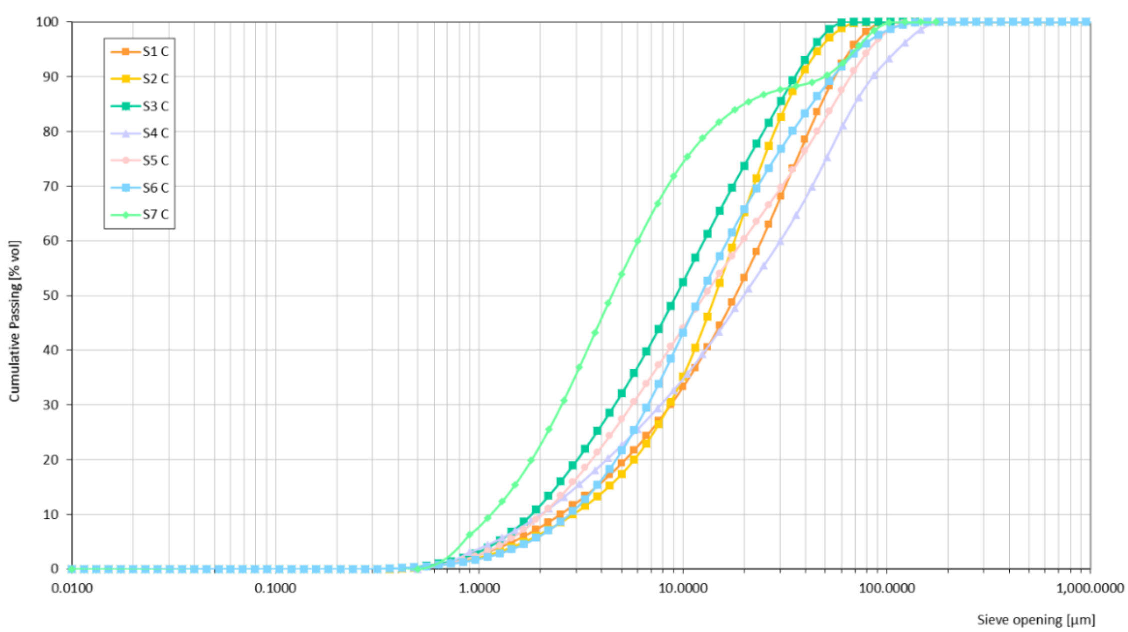


Figure 41. Particle size distribution of calcined sample powders finer than 125 µm

Table 18. Uncalcined and calcined samples D10 and D50 values and the ration of D50C to D50N

D [-]	D10	D50		D10	D50	D50 C / D50 N
S1 N [μm]	2.69	18.61	*S1 C [μm]*	2.50	18.06	0.97
S2 N [μm]	2.61	13.86	*S2 C [μm]*	2.90	14.38	1.03
S3 N [μm]	1.55	5.75	*S3 C [μm]*	1.81	9.25	1.60
S4 N [μm]	1.63	14.82	*S4 C [μm]*	2.01	19.93	1.34
S5 N [μm]	1.73	6.99	*S5 C [μm]*	2.04	12.76	1.82
S6 N [μm]	2.44	8.61	*S6 C [μm]*	2.77	12.18	1.41
S7 N [μm]	0.93	3.10	*S7 C [μm]*	1.13	4.48	1.4

4.2.3 Thermogravimetric Analysis TGA

The thermogravimetric analyses give an insight on how each of the materials transforms undergoing thermal treatment. At 125 – 135°C the process of water evaporation can be seen in the first peak across all the graphs for the 7 samples. The next peak occurring from 280 – 320°C is that of the burning of organic material from the samples and it can be observed in S1 (Figure 42), S3 (Figure 44) and S6 (Figure 47). This is due to the nature of the material as a gravel wash mud that is deposited in basins and can have traces of organic materials.

The dehydroxilation of kaolinite and illite which are present in all the investigated samples happens with a mass loss which is shown in the blue curve on the graphs. The range of the dehydroxilation temperature shown in endothermic peaks is dependent on the particle size and crystallinity of the clay and is mostly between 400 to 650°C for most kaolinites [292], but can also shift to higher temperatures depending on the mineralogical composition. These peaks correspond to the formation of an amorphous phase. S1 presents peaks of dehydroxilation at 530°C and 660°C for kaolinite and illite respectively. With a very similar composition and behavior S2 presents the same peaks at around 540°C and 680°C. S3 and S5 are the majorly kaolinitic content GWMs and their only main peak is at 540°C and 520°C respectively, indicating kaolinite dehydroxilation. The S4 diagram shows a further dehydroxilation peak at 780°C related to clinochlore and dolomite decarbonation, added to the two previous peaks at 570°C and 650°C for kaolinite and illite dehydroxilation respectively. S6 shows kaolinite dehydroxilation at 515°C and Illite dehydroxilation later closer to 700°C. The weight loss indication which also varies from one sample to another can also be seen reaching a constant after 700 – 800°C indicating full dehydroxilation.

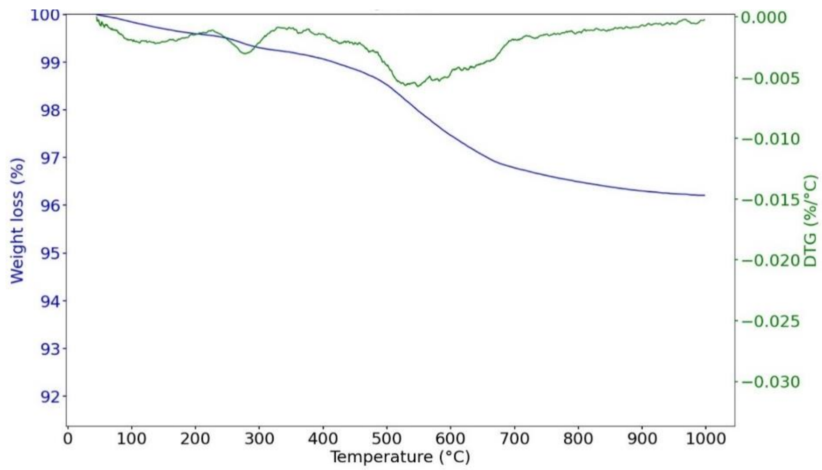


Figure 42. TGA / DTG graph in function of temperature for sample S1.

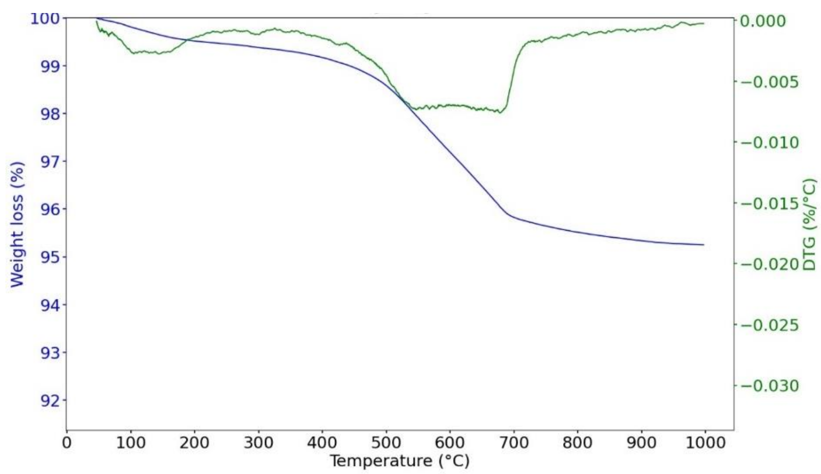


Figure 43. TGA / DTG graph in function of temperature for sample S2.

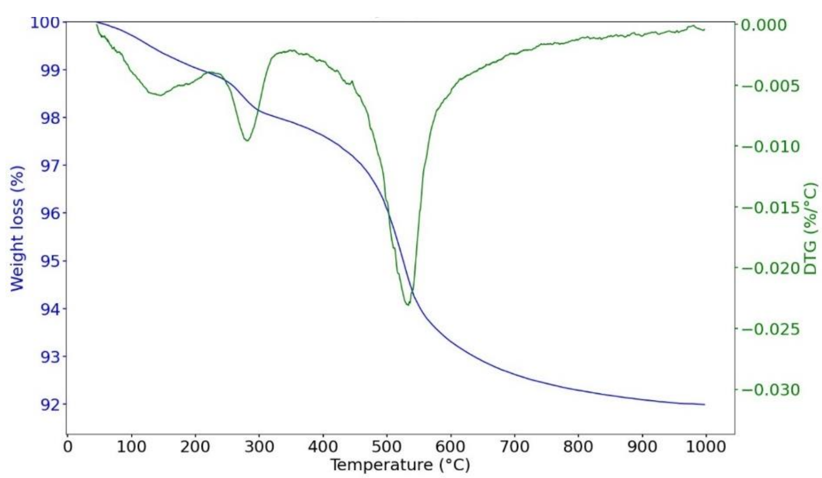


Figure 44. TGA / DTG graph in function of temperature for sample S3.

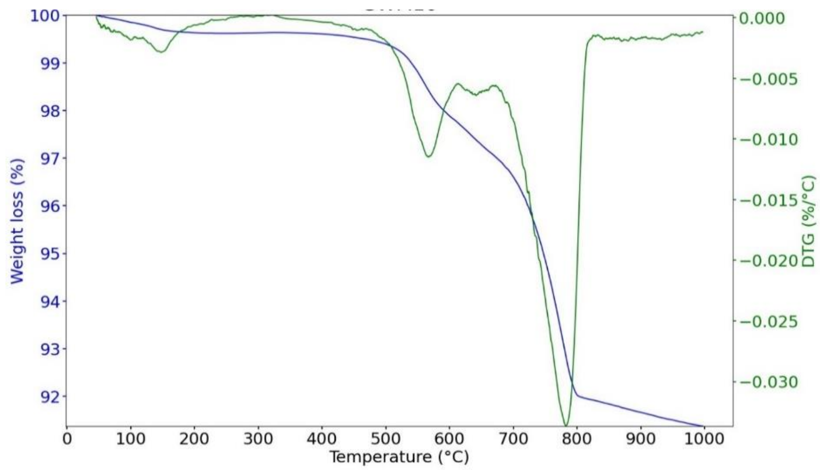


Figure 45. TGA / DTG graph in function of temperature for sample S4.

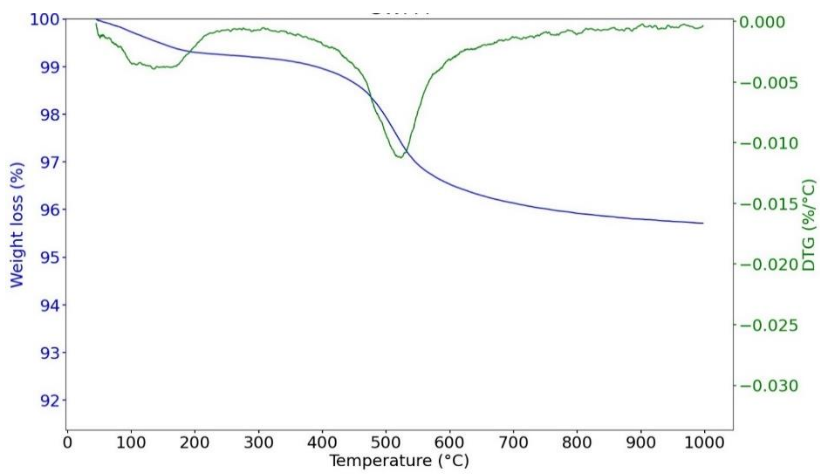


Figure 46. TGA / DTG graph in function of temperature for sample S5.

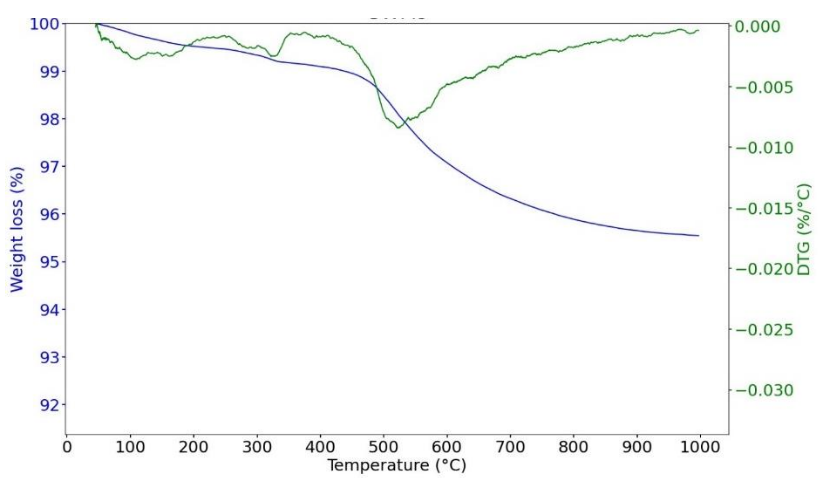


Figure 47. TGA / DTG graph in function of temperature for sample S6.

4.3 Determination of the pozzolanic activity

4.3.1 Direct testing methods: Frattini, Chapelle test, XRD analysis

The results of the Chapelle test are shown in figure 48, in mg of $Ca(OH)_2$ fixed per gram of material tested. For the majority of the tested materials an improvement is noticeable after calcination, mostly with a peak fixation observed at 650°C and 750°C. Some of the materials such as S1 and S6 present a deterioration at higher temperatures over 750°C that could possibly be explained by the sintering effect and the fact that kaolinitic phase minerals already have their dehydroxilation fully happening at lower temperatures [18], [292]. For S4 calcination does not seem to have any significant effect on increasing its natural pozzolanic status according to the Chapelle test.

Several authors have studied different types of metakaolin and calcined clays. For metakaolin samples the amount of portlandite fixed per gram of sample in Chapelle test varied from 657mg [293] to 1000-1400mg [294], [295], [296], [297] and 1600mg in certain hybrid improved samples [298]. As for calcined clays the values were around 584mg and 591mg for clays calcined at 700°C and 800°C respectively for the lower range and a higher range reaching to 948mg and 1028mg for the same two temperatures [299]. Others showed a range from 690mp to 1440mg for different series of clays [300], [301]. The results for the studied samples in this paper show that even with none to very little changes made to enhance the material's physical and or chemical properties, certain reactivity was still observed, albeit the studied samples were not all majorly kaolinitic.

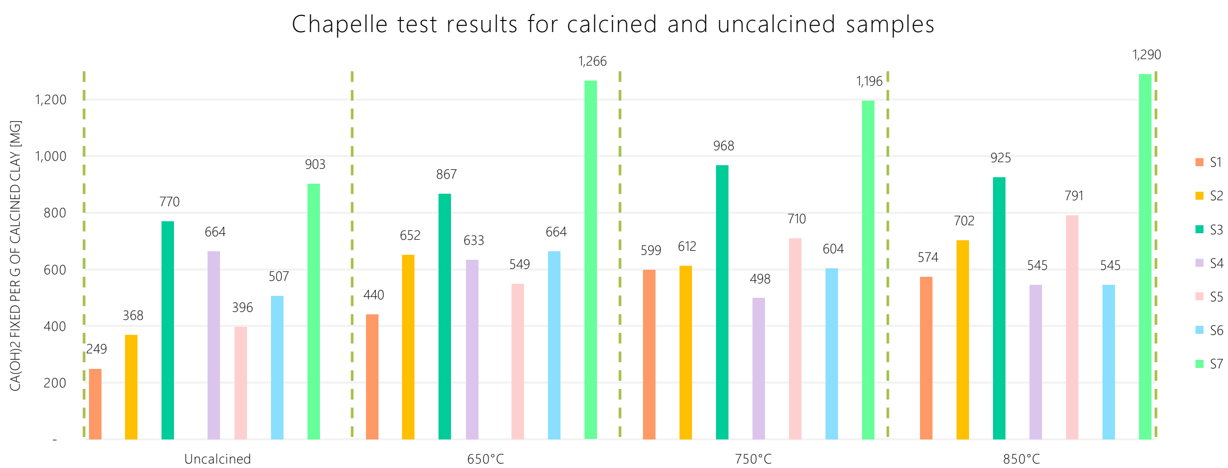


Figure 48. Chapelle test results as an average of 3 measurements rounded to the nearest decimal for all materials S1 to 7 uncalcined, and calcined at 650, 750 and 850 degrees. *(3<standard deviation<30)*

The Frattini tests that were carried out show that after calcination at 750 degrees the samples present pozzolanic activity according to the definition in the testing standard. In the natural state pre-calcination only S7 and S3 showed some degree of activity, both of which improved after calcination. At 650 degrees all materials except S2 show an improvement which can be noted by the plot points shifting downwards in the graph indicating a higher consumption of calcium hydroxide. S1 and S3 are the only two materials to show a retraction in pozzolanic activity in this test when calcined at 850 degrees.

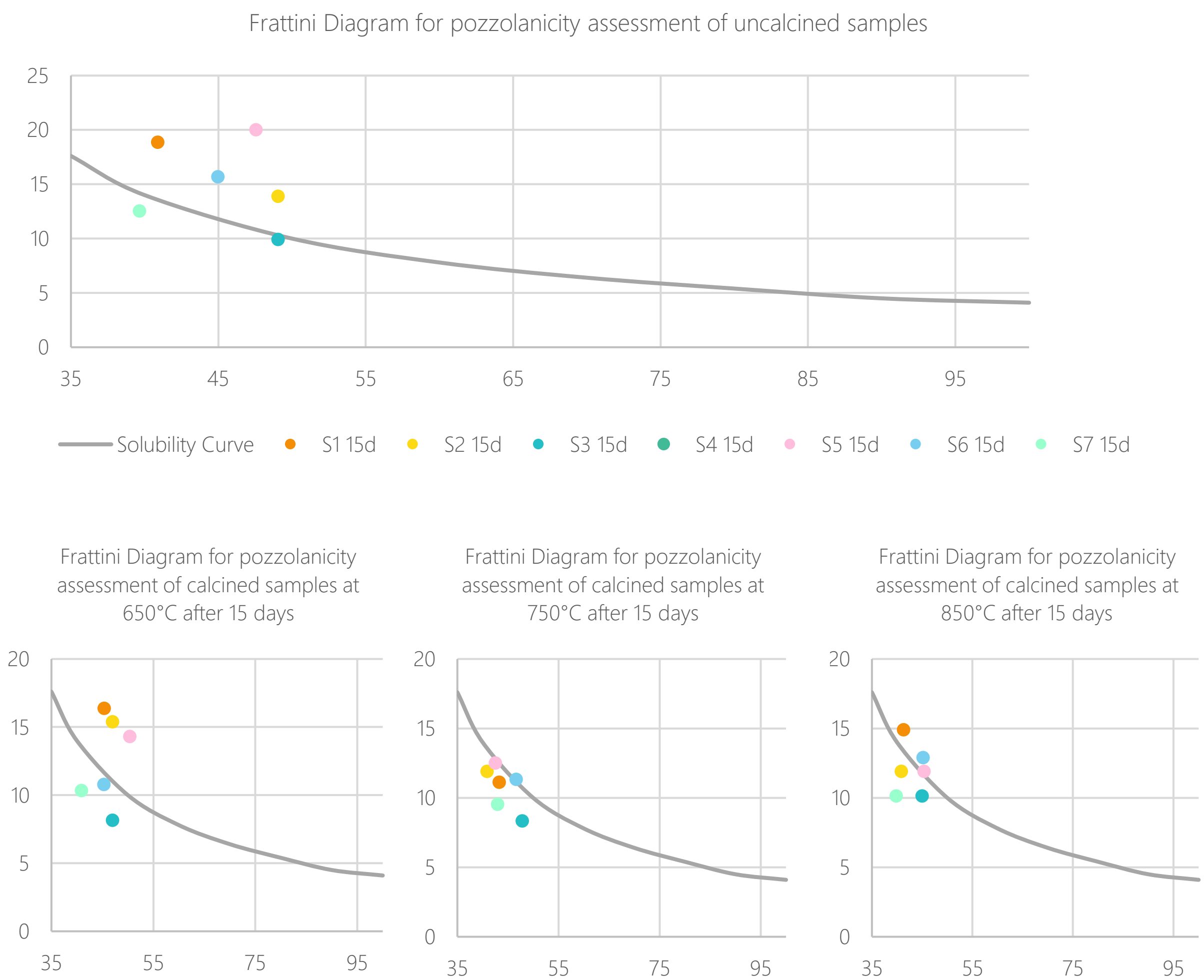


Figure 49. Frattini diagram for all uncalcined and calcined samples performed at 15 days (Horizontal axis OH^- concentration in mmol/L and vertical axis CaO concentration in mmol/L)

The XRD analyses were used to quantify the crystalline and amorphous phases in each of the materials and the results with the corresponding peaks are shown from Figure 50 to Figure 56 for S1, S2, S3, S4, S5, S6 and S7 respectively. It was important to identify at which temperatures the peaks of kaolinite disappear already and also essential in the quantification of the amorphous phase in each material sample as shown in the last column of Table 19. Most of the samples show an increase in amorphous phase after calcination accompanied by a decrease in kaolinite content to zero or very close to zero indicating a full dehydroxilation. The comparisons can be drawn on the disappearance of kaolinite, the shifting of the peaks of illite, and the amorphous and crystalline phases. S4 and S6 present no kaolinite minerals after 750 degrees as well as a gradual decrease in illite as the temperature increases. In terms of composition all the uncalcined materials show quartz, feldspar, kaolinite and muscovite/illite and in the case of S4 some traces of chlorite, calcite and dolomite. The full ranges and approximate quantities calculated through input from the XRD raw data are presented in Table 19.

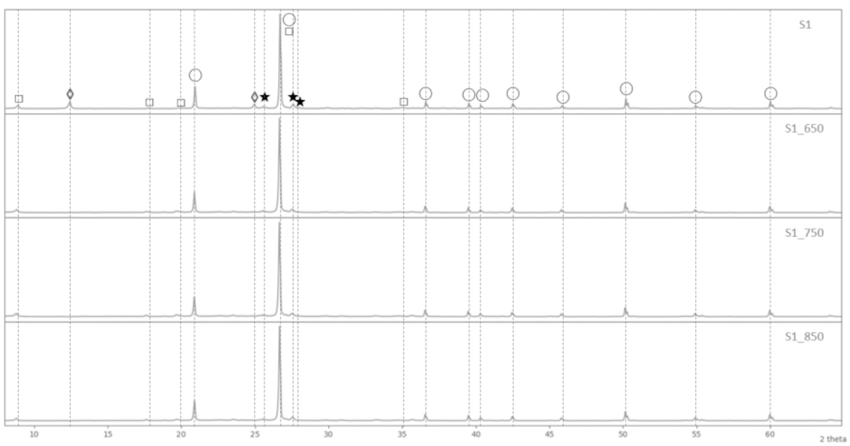


Figure 50. X-ray diffractogram of S1 uncalcined and calcined samples.

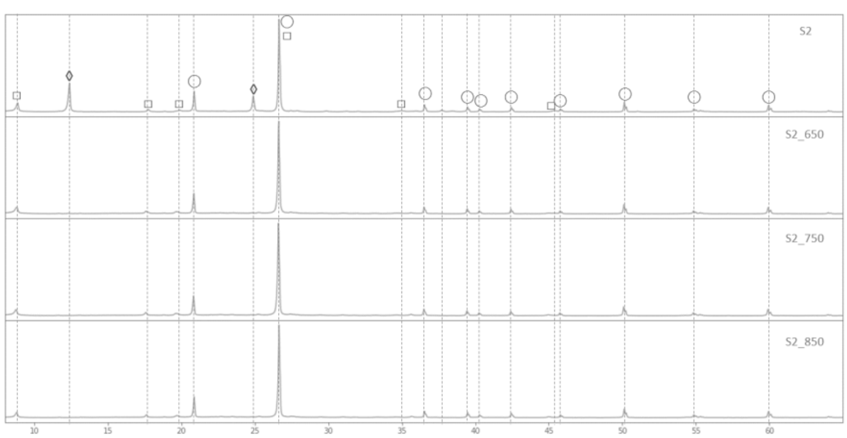


Figure 51. X-ray diffractogram of S2 uncalcined and calcined samples.

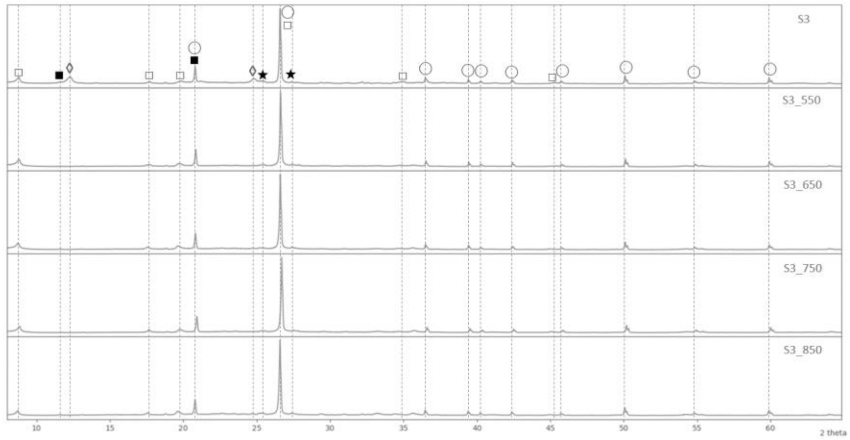


Figure 52. X-ray diffractogram of S3 uncalcined and calcined samples (including intermediate stage at 550°C).

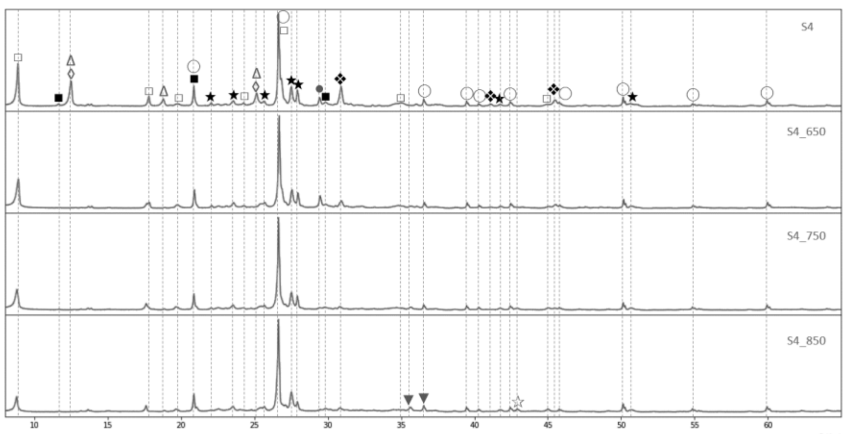


Figure 53. X-ray diffractogram of S4 uncalcined and calcined samples.

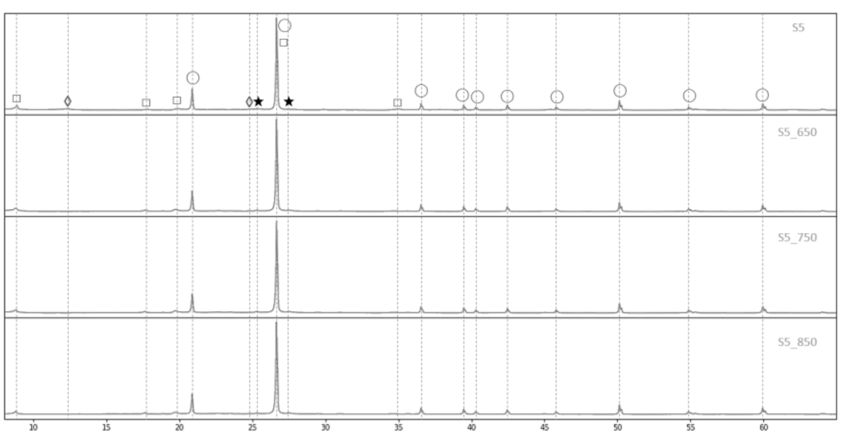


Figure 54. X-ray diffractogram of S5 uncalcined and calcined samples.

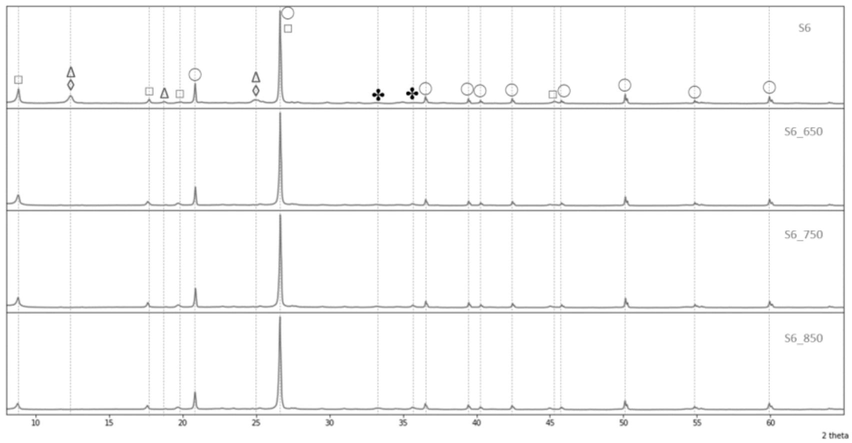


Figure 55. X-ray diffractogram of S6 uncalcined and calcined samples.

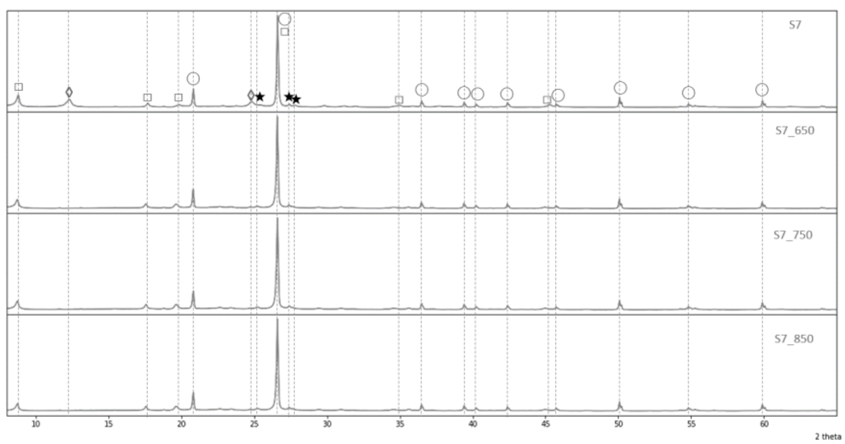


Figure 56. X-ray diffractogram of S7 uncalcined and calcined samples.

◯ - quartz; ◊ - kaolinite; □ - muscovite/illite; ★ - feldspars (orthoclase, microcline, albite, sanidine); ■ - gypsum; Δ – clinochlore;
● - calcite; ❖ - dolomite; ☆ - periclase; ▼ – forsterite; ✤ Hematite

Starting from the characteristic peaks and the raw data of the XRD analysis, the visual patterns providing qualitative insight into the crystalline and non-crystalline phases present in the samples, a quantitative phase analysis was derived from Rietveld refinement in MATLAB detailing the approximate _/ relative proportions of quartz, clay minerals, and amorphous content in each sample (Table 19).

Table 19. Mineralogical composition in % per sample for quartz, clay minerals, and amorphous phase.

	Quartz	Clay minerals			Amorphous phase
		Kaolinite	*Muscovite/Illite*	*Clinochlore*	
	○	◊	□	Δ	-
S1					
S1_nat	67.7±0.5	13.6±0.5	7.4±0.5	-	14.7±6.5
S1_650	76.5±0.6	2.2±0.3	9.1±0.4	-	23.3±5.2
S1_0	77.2±0.5	1.5±0.2	10.6±0.4	-	25.0±4.4
S1_850	79.1±0.5	1.1±0.2	9.7±0.4	-	20.1±4.5
S2					
S2_nat	64.1±0.9	23.6±0.9	12.3±0.6	-	20.7±5.6
S2_650	81.7±0.5	6.8±0.3	11.5±0.4	-	25.6±8.9
S2_750	82.8±0.5	5.7±0.3	11.5±0.4	-	30.1±4.8
S2_850	83.9±0.4	7.7±0.3	8.4±0.3	-	26.2±3.2
S3				-	
S3_nat	49.4±0.7	29.9±0.7	14.5±0.9	-	35.4±7.5
S3_550	65.1±0.9	3.7±0.4	25.3±0.8	-	42.2±8.4
S3_650	67.8±0.9	4.4±0.4	24.0±0.7	-	40.8±6.2
S3_750	67.6±1.0	2.4±0.4	26.4±0.9	-	32.7±4.7
S3_850	67.0±0.3	1.6±0.2	26.2±0.2	-	37.9±6.8
S4					
S4_nat	19.2±0.5	10.8±0.5	23.9±1.0	14.4±0.5	21.3±7.0
S4_650	28.9±0.6	0.6±0.2	21.9±0.7	6.7±0.4	23.5±7.0
S4_750	34.7±0.6	-	19.6±0.7	2.1±0.3	26.8±5.3
S4_850	39.5±0.6	-	10.7±0.6	3.0±0.4	27.6±7.6
S5				-	
S5_nat	77.7±0.6	4.9±0.3	12.7±0.6	-	27.5±6.5
S5_650	86.0±0.5	-	6.4±0.4	-	26.0±7.8
S5_750	86.1±0.5	-	8.2±0.4	-	24.1±4.1
S5_850	86.4±0.5	-	7.8±0.4	-	26.1±4.2
S6					
S6_nat	45.75±0.48	22.52±0.43	18.58±0.61	11.94±0.36	25.79±3.65
S6_650	65.14±0.55	0.44±0.11	29.98±0.57	0.67±0.12	25.88±3.42
S6_750	69.19±0.53	-	26.33±0.52	-	27.86±5.47
S6_850	72.70±0.57	-	21.92±0.56	-	25.67±4.83
S7					
S7_nat	44.0±0.7	23.7±0.9	28.8±0.7	-	24.8±7.4
S7_650	70.1±1.0	6.3±0.7	22.5±0.8	-	30.7±4.6
S7_750	68.3±0.1	7.4±0.7	22.2±0.8	-	32.4±4.8
S7_850	70.8±0.9	6.9±0.7	21.0±0.7		27.6±7.7

An analysis of this table and the data it contains on the clay phase enables the general conclusion that as the calcination occurs, the kaolinite content disappears and transforms into MK, as well as a certain parcel of illite becoming amorphous.

4.3.2 Indirect testing method: compressive strength.

Complementary to the direct testing methods described and evaluated previously, an indirect method to assess pozzolanic activity can be the analysis of the strength activity index (SAI). According to ASTM C618-15, regarding mechanical strength, a material is considered pozzolanic if a mortar with 20% cement replacement ratios at 75% of the reference. [302]

4.3.2.1 Binders / paste mixtures

In the next series of bar graphs the compressive strength of binder / paste mixtures are presented for curing ages of 7, 28, 56 and 90 days for each of the 7 materials tested.

S1, a material moderate in kaolinite content shows the best mechanical performance with 79 MPa at 90 days equivalent to an SAI of 110. Among the three temperatures tested 750°C seems to be the optimal, however the SAI is already at 89 at 650°C which is greater than 75% and therefore the definition of pozzolanicity is satisfied [302].

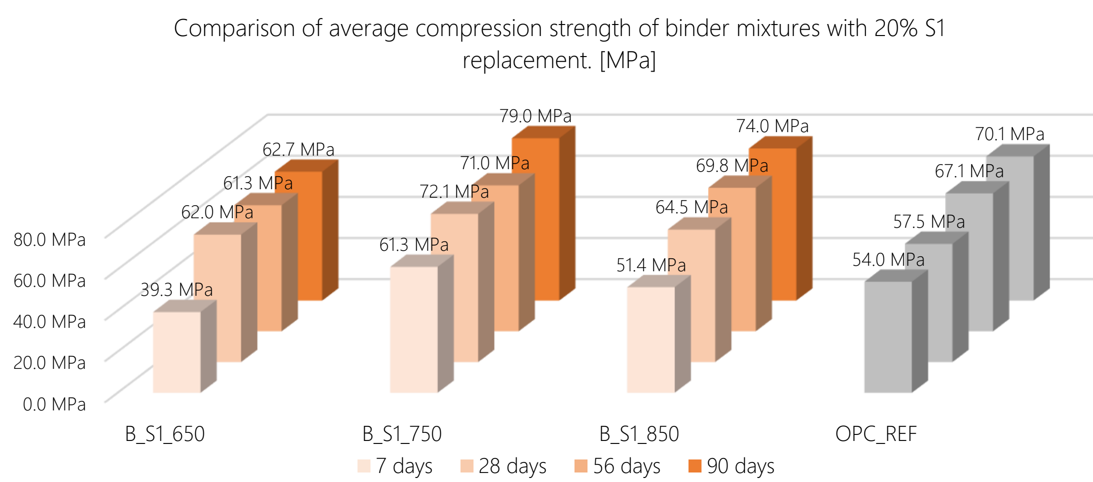


Figure 57. Compressive strength evolution for 20% S1- 80% cement paste at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

For S2 the evolution of strength was virtually the same across all temperatures concentrating in binder mixtures with the SAI at around 90, Figure 64. This suggests that the influence of temperature on dehydroxilation was limited and can be explained by the mineralogical composition of the material and the x-ray diffractogram showing that kaolinite peaks disappeared and became constant already at 650 degrees, Figure 51 which indicates that the full pozzolanicity potential was achieved already at the lower end of the temperature treatment spectrum.

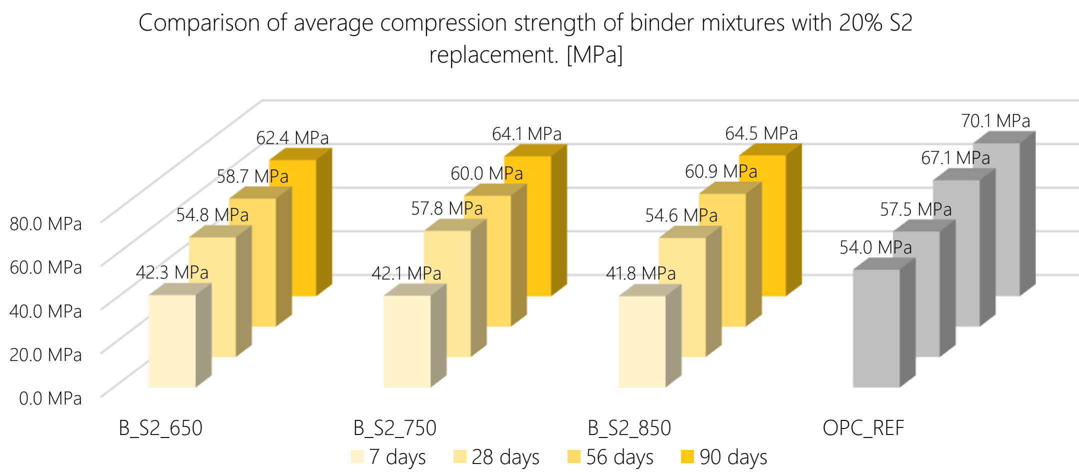


Figure 58. Compressive strength evolution for 20% S2 - 80% cement paste at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

S3 binder mixtures show an increase in strength from 650°C to 750°C but then a limited improvement at 850°C suggesting that the optimal temperature for thermal treatment is around 750°C (Figure 58). The pattern is also respected throughout the whole evolution in curing time from 750°C. When treated at 650°C the maximum strength is reached at 28 days and then stays constant until the 90 days.

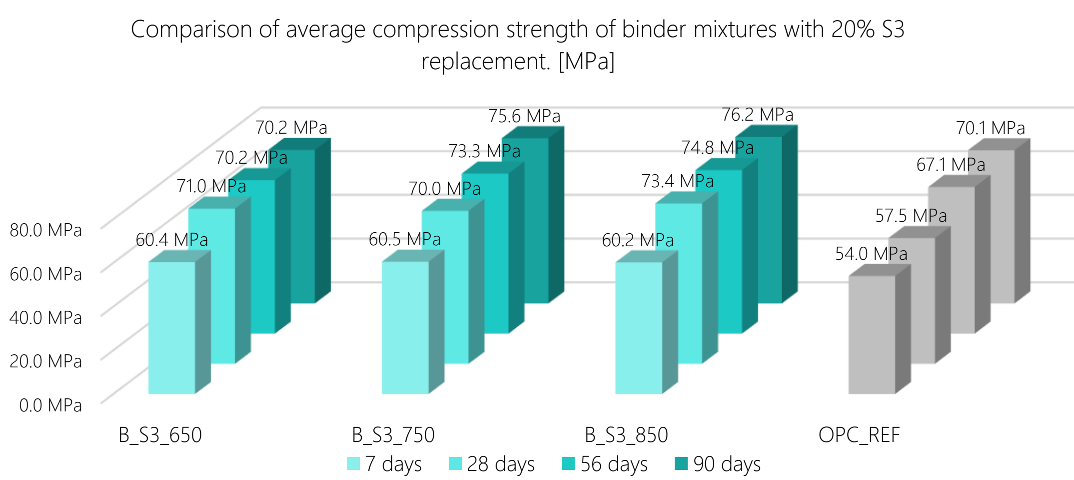


Figure 59. Compressive strength evolution for 20% S3 - 80% cement paste at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

S4 shows the same performance for the 650 and 750°C temperatures and a slight increase in strength of around 7% at 850°C (Figure 59). However, as it is the case with other samples the 90 days resistance at 87% for 650°C is already considered pozzolanic (Figure 64).

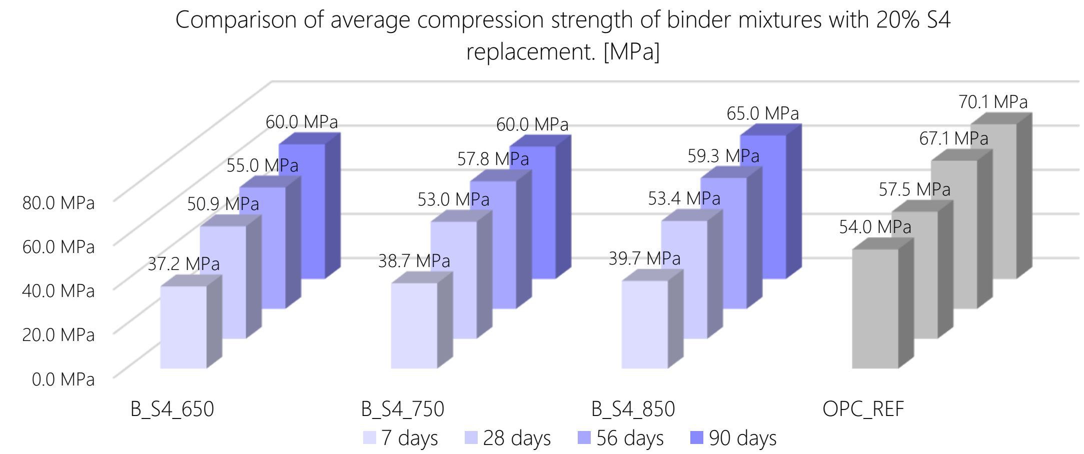


Figure 60. Compressive strength evolution for 20% S4 - 80% cement paste at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

S5 shows an incremental progression in strength across the three temperatures starting at 64 MPa at 650°C reaching 67MPa at 750°C all the way up to 73MPa at 850°C as can be seen in the graph (Figure 61). However, the 650°C treatment is already at an SAI of 92 (Figure 64).

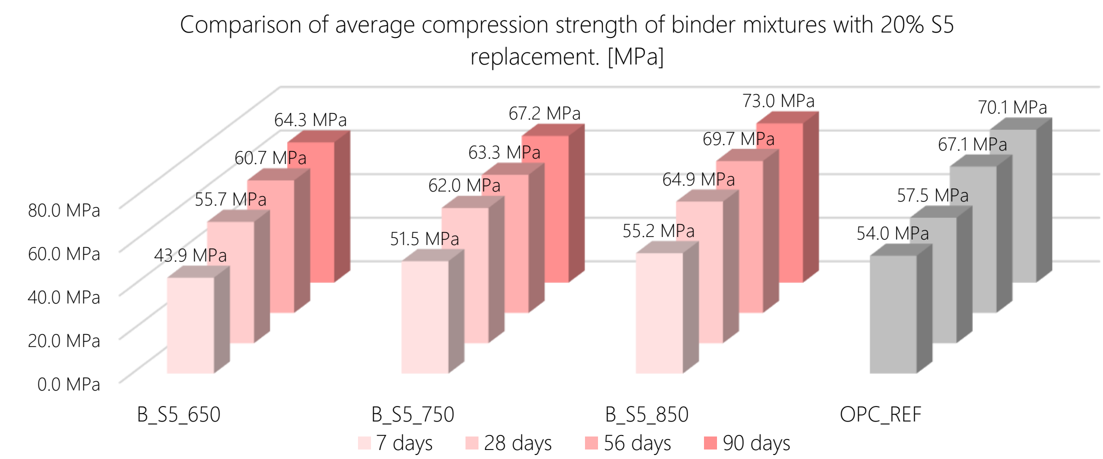


Figure 61. Compressive strength evolution for 20% S5 - 80% cement paste at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

Similarly to S4, S6 shows an increasing strength measurement the higher the temperature. When compared to the other materials it has the least strength in absolute value (Figure 62). However, the SAI is still over the 75% threshold in the case of the 750 and 850°C treated powders as can be seen in Figure 64.

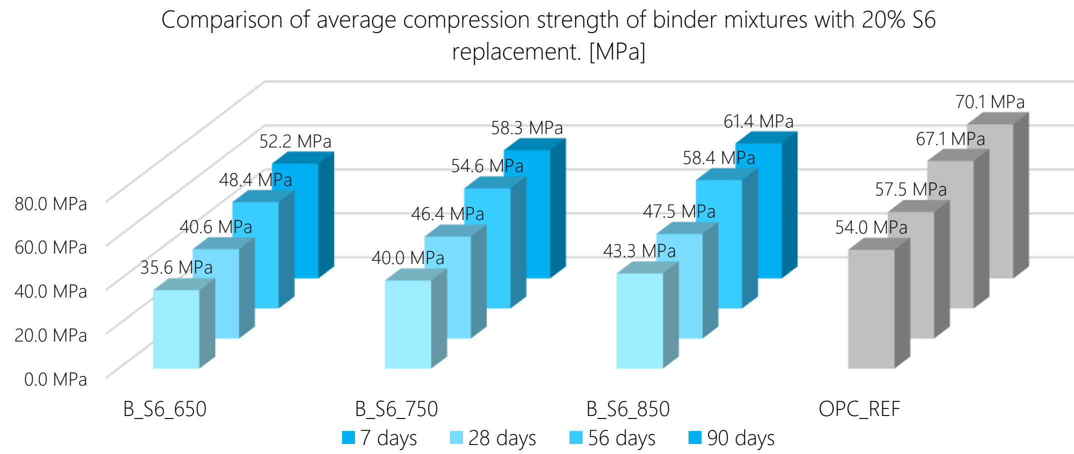


Figure 62. Compressive strength evolution for 20% S6 - 80% cement paste at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

S7 at 650°C is the highest scoring across the whole range of materials studied when it comes to compression strength. The binder mixtures show a strength at 90 days of 72MPa equivalent to an SAI of 103. A slight strength increase at 750°C followed by a decrease at 850°C with SAIs of 103 and 95 respectively, both high above 75 (Figure 64).

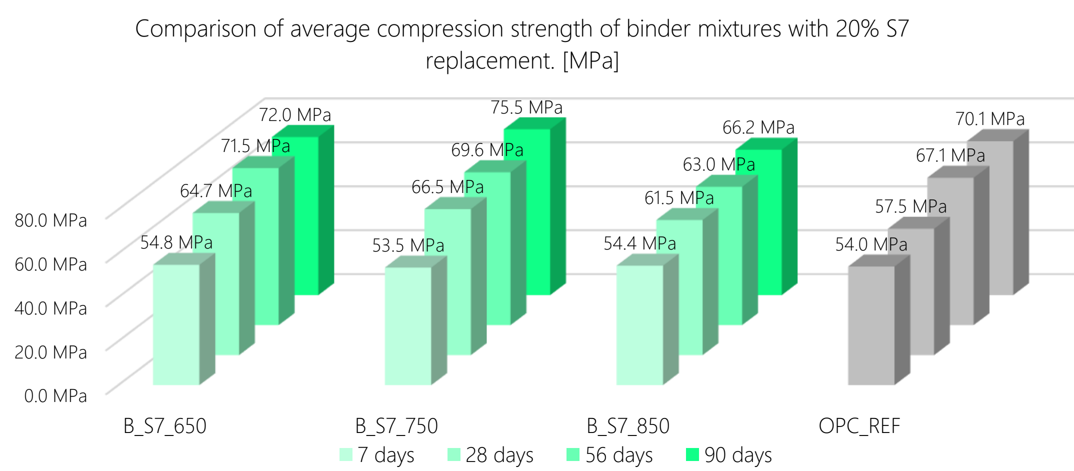


Figure 63. Compressive strength evolution for 20% S7 - 80% cement paste at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

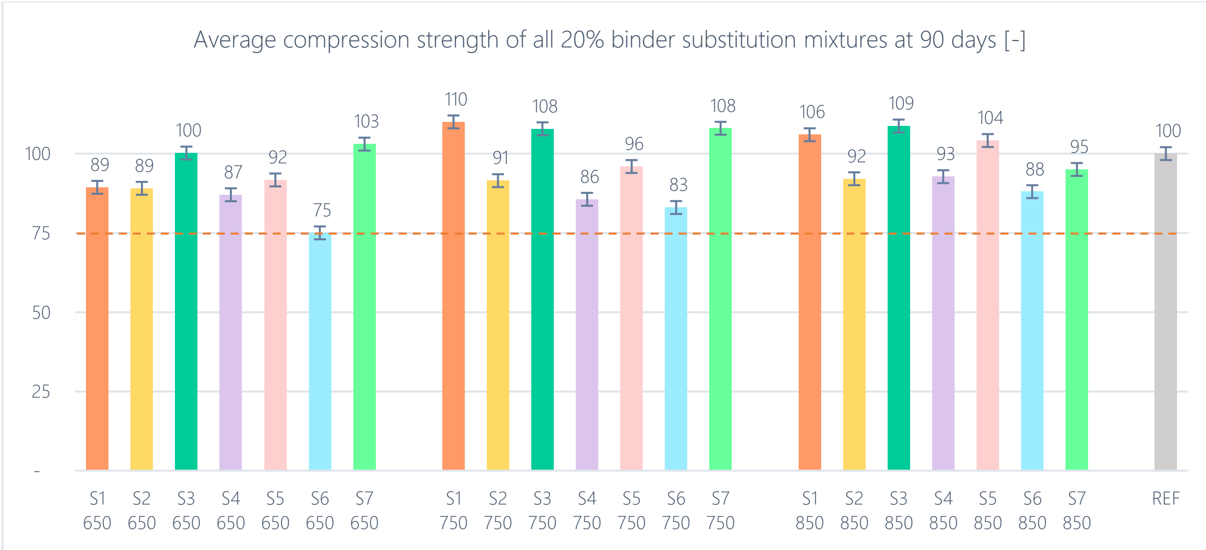


Figure 64. SAI averages for all binder mixes at 90 days grouped per calcination temperature 650°C, 750°C and 850°C.

4.3.2.2 Mortar mixtures

The mortars prepared were measured for mechanical strength in the same way as the paste/binder mixture prisms, and the results are shown in the graphs of this section. S1 mortars followed the same trend as the binders although with a less significant difference between the temperatures, however still having the highest strength at 750°C (Figure 65).

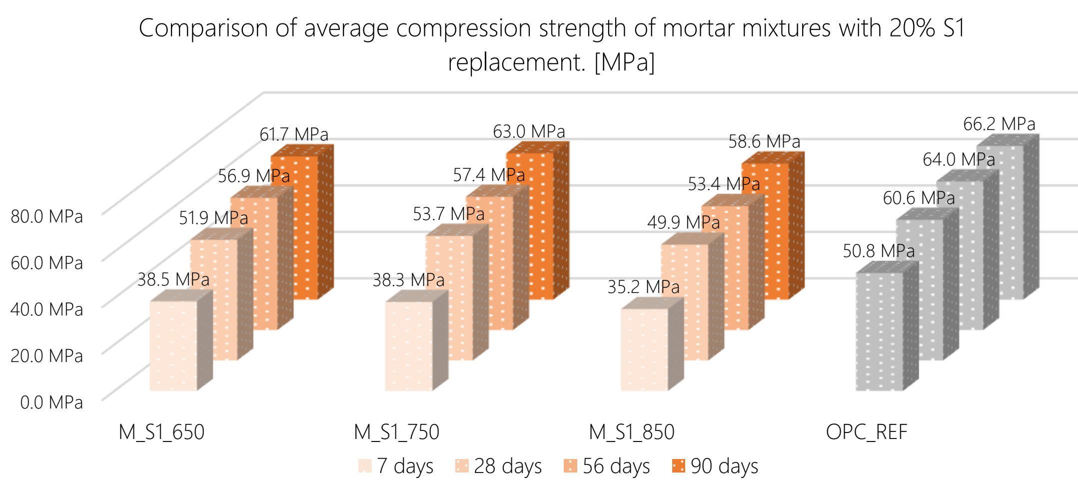


Figure 65. Compressive strength evolution for 20% S1 - 80% cement mortar at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

S2 mortar specimens (Figure 66) can also be compared to the paste/binder specimens of the same material. The addition of sand in the mortar specimens does not create a loss of strength when compared to the binder mixtures, unlike for the other investigated materials. This means that the SCM-OPC matrix is strong enough to create a network that keeps and enhances the strength properties of the binder around the sand particles. At a temperature of 650°C, consistent with the TGA peaks of dehydroxilation (Figure 43), S2 is already at an optimal calcination temperature. The increase of 200°C in calcination temperature to 850°C only produced a limited gain in strength at an order of 2% from an SAI of 98 to 100 (Figure 72).

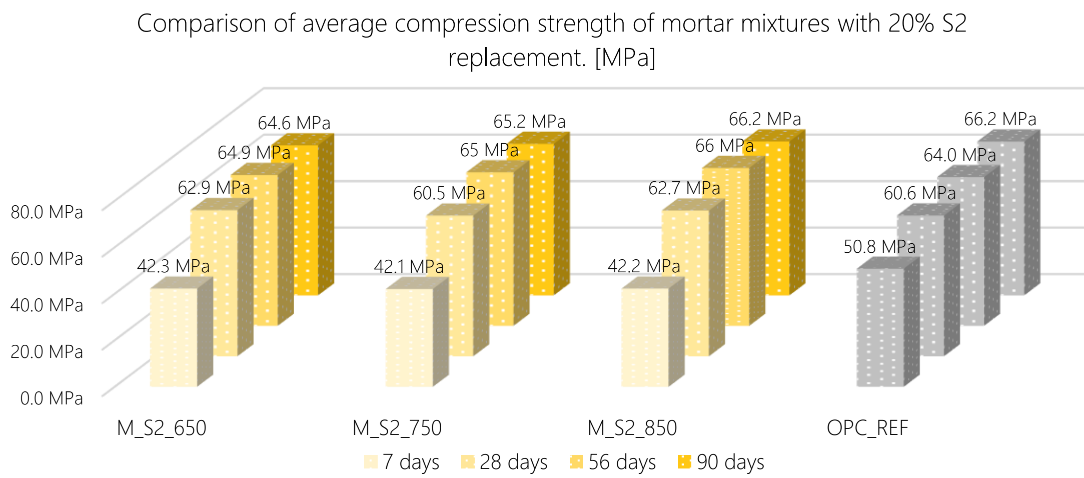


Figure 66. Compressive strength evolution for 20% S2 - 80% cement mortar at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

For S3 the calcination temperature had virtually no difference on strength development and the values are all comparable across curing age and calcination parameters (Figure 67). S3 is a majorly kaolinitic material and one can conclude from the TGA analysis that dehydroxilation was complete at 650°C and a higher calcination temperature did not bring any advantage.

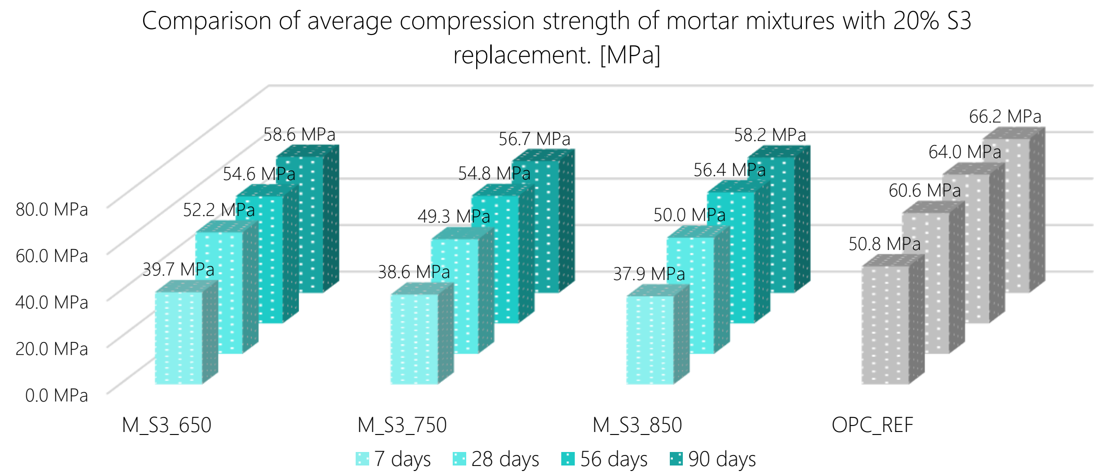


Figure 67. Compressive strength evolution for 20% S3 - 80% cement mortar at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

S4 mortars score a bit lower when compared to others, and they show similar performance at 650 and 750°C but an improvement at 850°C. This is consistent with the TGA data (Figure 45) in which another endothermic peak indicating a further dehydroxilation only occurs at 780°C. S4 contains low kaolinite contents when compared to the other samples and has phases with chlorite and dolomite as well, unlike the other materials that are mostly kaolinitic and illitic. So, this explains the loss in strength *vis-à-vis* the other higher resistance samples (Figure 68).

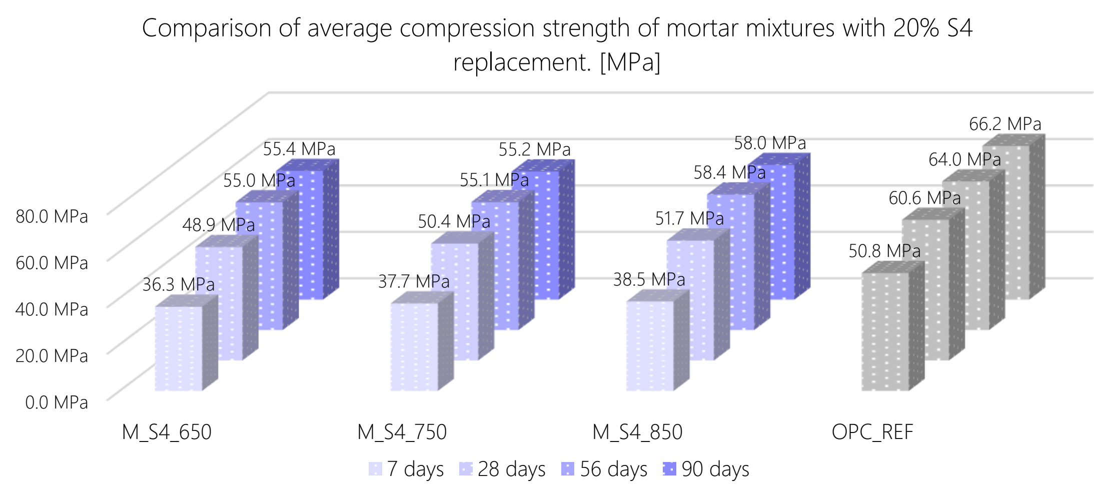


Figure 68. Compressive strength evolution for 20% S4 - 80% cement mortar at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

S5, a material with relatively high quartz content, presents a performance similar to that of S4 and S6 but with a step increase of roughly 1 MPa for each temperature increment (Figure 69). The SAI at 90 days is at 81%, 82% and 84% for 650°C, 750°C and 850°C respectively (Figure 72). Due to the high quartz content, the pozzolanic effect is less than in the other samples.

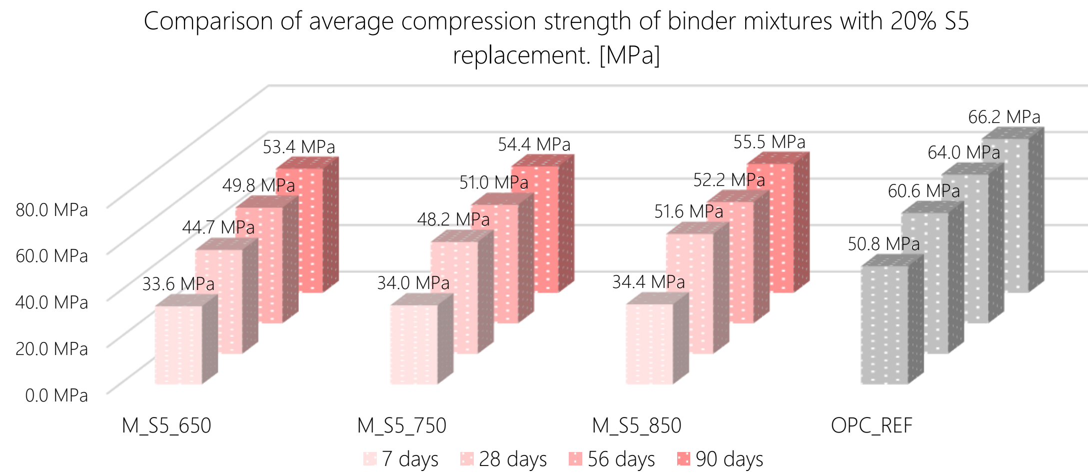


Figure 69. Compressive strength evolution for 20% S5 - 80% cement mortar at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

S6 mortars also follow the trend of increase in resistance with the increase in temperature (up to approximately 750°C, Figure 70). However, the SAI at 650°C falls shortly into being considered pozzolanic at that temperature with a 72 (Figure 72) while the minimum needed is 75.

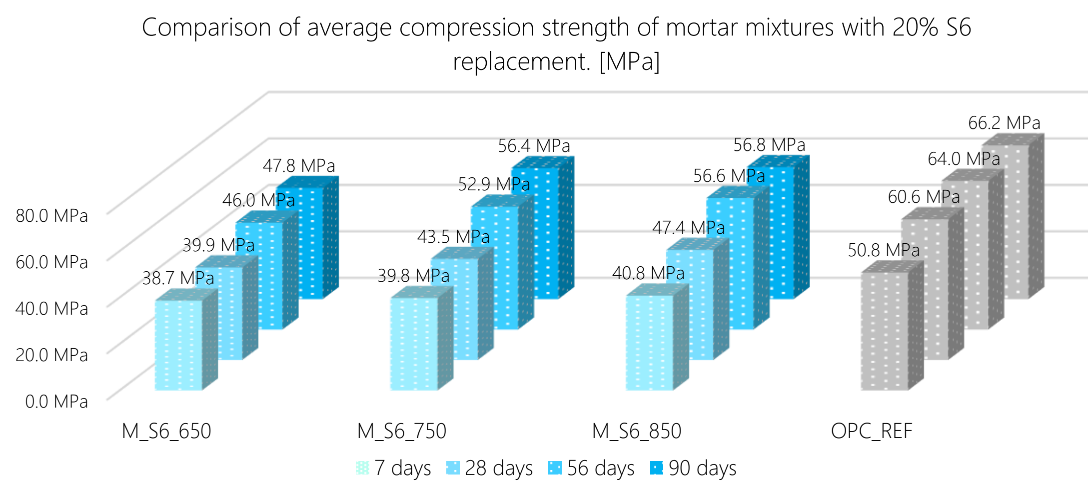


Figure 70. Compressive strength evolution for 20% S6 - 80% cement mortar at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

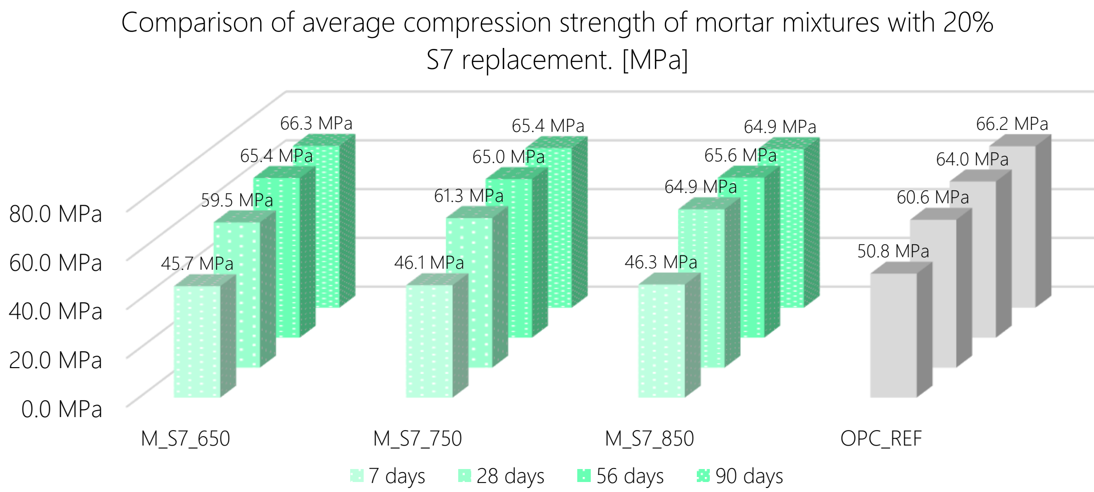


Figure 71. Compressive strength evolution for 20% S7 - 80% cement mortar at a curing age of 7, 28, 56 and 90 days compared to 100% OPC reference.

The highest resistance to compression of all mortar specimens is evidenced in S7, particularly at 650°C reaching 66.3MPa strength at 90 days (Figure 71). The results can be explained as a combination of physical and chemical properties of this material which grant it a good performance as an SCM. S7 is considered pozzolanic with the highest consumption of portlandite in Chapelle test compared to all other studied samples (Figure 48) and having the finest particle distribution with a d50 of 4.48 µm after calcination (Figure 41).

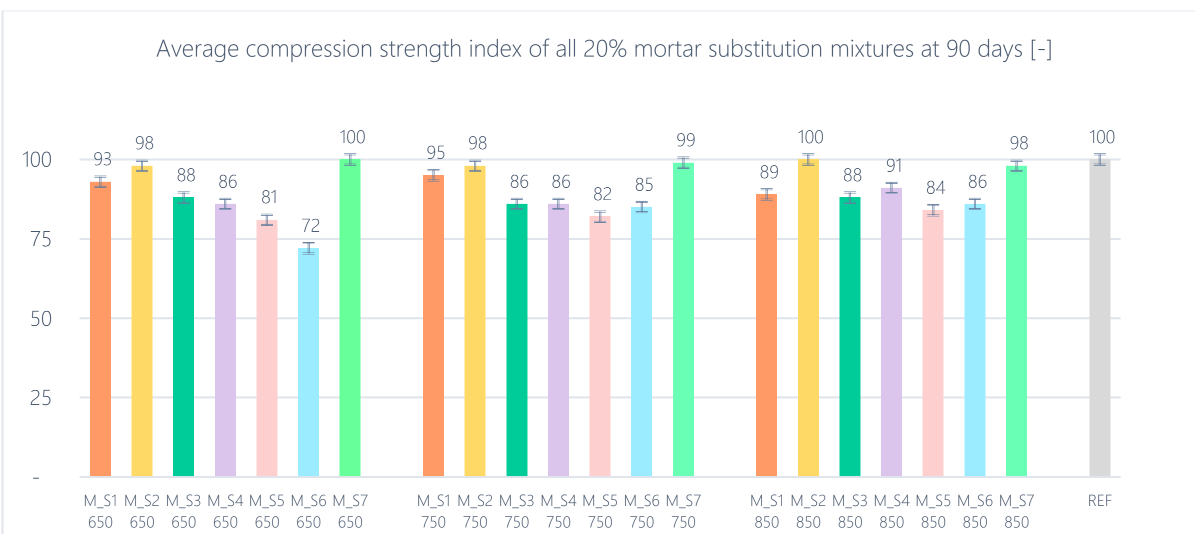


Figure 72. SAI averages for all mortar mixes at 90 days grouped per calcination temperature 650°C, 750°C and 850°C, reference sample with 100% OPC in grey.

In conclusion, the data reveals that calcination temperature plays a crucial role in optimizing the pozzolanic performance of SCMs, with an optimal window generally around 750°C for most materials, although some—such as S2 and S7—already exhibit strong performance at 650°C. For binder mixtures, materials like S1 and S7 achieved high compressive strengths and SAIs (with S1 reaching 79 MPa at 90 days and S7 maintaining over 70 MPa), demonstrating that a moderate to high kaolinite content coupled with fine particle distributions significantly enhances reactivity. In contrast, S5, with its higher quartz content, shows a more gradual strength gain with increasing temperature, indicating a less pronounced pozzolanic effect. Mortar tests further illustrate that the inclusion of sand does not necessarily diminish strength, as seen with S2, while for others the mortar performance mirrors that of the binder but with slightly lower absolute values. Overall, these results underscore the importance of tailoring calcination conditions to the specific mineralogical composition of the material to maximize long-term compressive strength and ensure the achievement of pozzolanicity.

4.4 The pozzolanicity potential index

As a commitment to adding value to the industry in the Greater Region and helping towards the transition to a more circular built environment by tackling the material scale challenges of the spectrum, this paper proposes an index based on 4 parameters that are easily testable where university labs can help their industrial partners without the need for high-tech laboratory analyses. The parameters are (1) physical properties covering particle size distribution and blaine fineness, (2) chemical reactivity comprising Frattini and Chapelle tests, (3) environmental impact centered around the temperature of calcination, and finally (4) mechanical strength. Each one of those parameters carries a total weight of 1 and the attributed score to each category is defined for each range from 1 to 5 (Table 20. Parameters used for the pozzolanicity potential index.).

Table 20. Parameters used for the pozzolanicity potential index.

Score	Fineness *µm, %*	Blaine *cm²/g*	Frattini -	Chapelle *mg/g*	Temp *°C*	Compression strength *28 days SAI in %*
1	d > 45µm < 55%	2000	first percentile	0-250	>1000	<35
2	d > 45µm < 45%	4000	second percentile	251-500	950	55
3	d > 45µm < 35%	6000	solubility curve line	501-750	850	75
4	d > 45µm < 25%	8000	fourth percentile	751-1000	750	95
5	d > 45µm < 15%	10000	fifth percentile	1000+	<650	115+

To calculate the index for each material, the average result of all measurements that belong to a certain parameter was taken as a final value and fitted into a linear curve constructed from the fitting of the five points in Table 20 with the score points 1 to 5 corresponding to each of the studied parameters and then weighted as shown in Table 21. The results for each parameter are shown in Figure 73.

The chosen parameters are the ones that are either a source or an outcome of pozzolanicity. Therefore, the particle size effect was distributed for fineness and Blaine value, the direct pozzolanicity was distributed among Frattini and Chapelle tests, each with a 0.5-point weighting, the optimal calcination temperature was assigned a value of 1 and the indirect pozzolanicity given by the strength activity index a factor of 1 as well.

Table 21. Weighting coefficients for each parameter cluster.

Parameter	*Fineness*	*Blaine*	*Frattini*	*Chapelle*	*Temperature*	*Compression strength (mortars)*
Weight	*0.5*	*0.5*	*0.5*	*0.5*	*1*	*1*

The relationship between the parameters is nonlinear and governed by other complex constraints as discussed in the results presented in the earlier sections. However, having a starting point for decision making and taking into consideration different parameters helps sketch an initial picture to the industrial stakeholders on which of their waste materials can be deemed of value and therefore should be considered to have a valorization potential. Therefore, the model is recommended as a starting point of analysis for specific clay-based construction wastes that have never been tested and is limited in that sense. In this field it is rarely the case to have a model that applies to all interactions as some of the aspects of concrete hydration and strength evolution are still research subjects as it has been shown in the literature review. Starting from a pragmatic point of view, that might appeal for industrial partners who might not want to spend so much on initial testing of materials of unknown potential, this can be a solid and cost-effective solution that can be developed with university labs who have the expertise and machinery to do so without overburdening parties who do not have access and know-how of such testing methods that can be deemed complex.

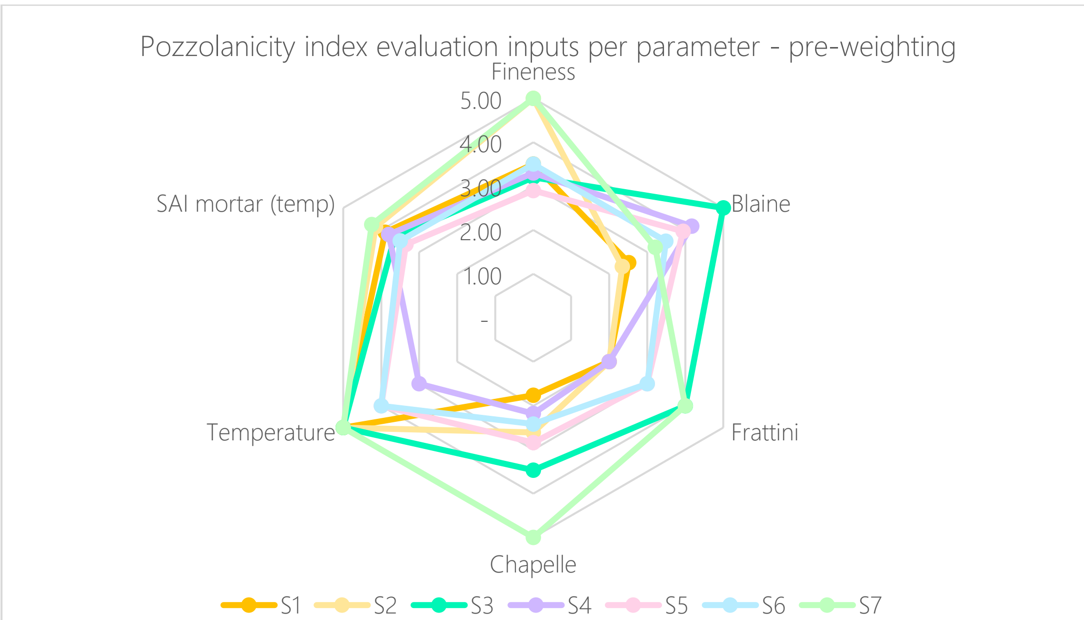


Figure 73. The pozzolanicity index inputs per parameter from 0-5 prior to weighting.

In this case, the scale works in the following manner: the closer the overall score is to 5 the better the chances of the tested material becoming of value, and the closer to 1 the worse is its expected performance in terms of being potentially used as an SCM. The scores of the different samples studied in project CO2REDRES are shown in Figure 74.

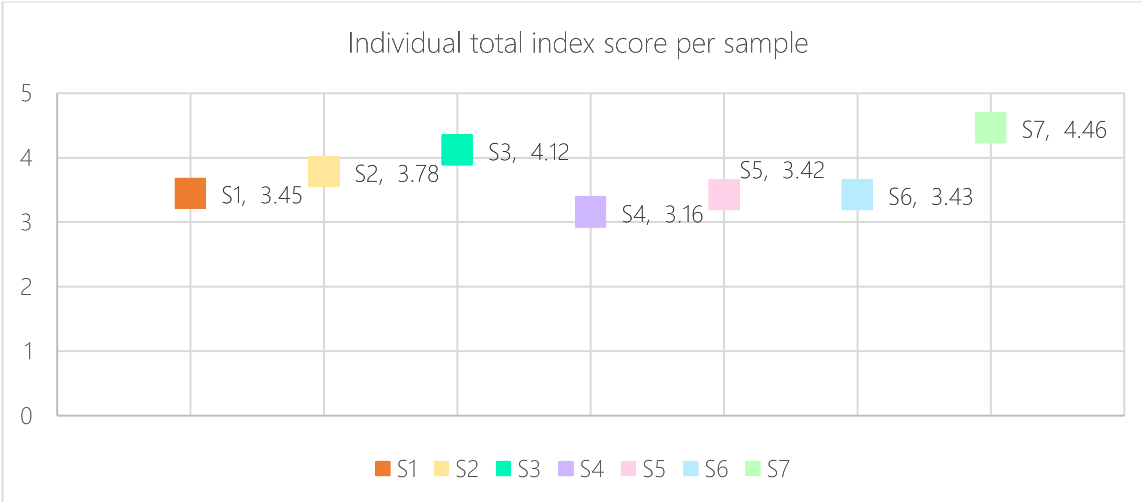


Figure 74. The pozzolanicity index results for CO2REDRES materials

4.5 Discussion of results in the context of research questions.

4.5.1 Recap of project CO2REDRES

In the initial phase of the project, researchers from the University of Trier focused on identifying potential materials that are either secondary raw materials or industrial waste at the industrial facilities of the strategic partners of the project. The cooperation partners were invited to send samples of industrial waste and secondary raw materials. After an initial screening of 34 materials, and the exact identification of the different clay minerals that play an important role in cement reactivity, the materials chosen for the next step at the University of Luxembourg. Here, the physical and chemical properties of these materials were studied to determine the feasibility of using those as an SCM concept replacing up to 20% of OPC in different pastes and mortars. The results of this part were presented in the previous section and will be further discussed here and linked to the rest of the project and the literature findings. Posteriorly, the University of Lorraine chose to study Limestone Calcined Clay Cement (LC3) formulations to replace 50% of clinker, and to prepare the binders, a characterization study of the components and an optimization of the formulations were necessary. In the end 5 of the materials tested by the University of Luxembourg were used and the evolution of their mechanical performance over time was analyzed showing promising results and validating the applicability of these formulations as well as the results previously obtained during the project. In the last step, the University of Liege performed an LCA to analyze the impacts of the mortars characterized by the use of mineral additions taking the materials of project CO2REDRES into the model. Their research concluded that the benefit in terms of climate change impact category is of the order of 25% for mortars with 30%wt substitution by calcined or fresh mineral additions.

By recovering gravel washing sludge, this project not only contributed to the transition towards sustainability of the cement industry, but also reduced the environmental impact of gravel mining. The sludge was collected from methodological operators (industrial partners), then dried and ground into fine powders, and heated to a temperature of up to 850°C, about half that of the ordinary Portland cement manufacturing process where kiln temperatures reach 1400°C. After studying the physical and chemical properties of the powders, they were incorporated into mixtures with cement to form pastes and mortars whose compressive strength was then determined. The pozzolanicity and mechanical strength of the various additions were also fully investigated. The broad conclusion was that all the materials selected in phase one were suitable for use as additions. The compressive strength already reached a satisfactory value at around 650°C for some of the materials, while others had better performance at higher temperatures including 750°C.

4.5.2 Overview of the experimental findings on composition, pozzolanicity and strength.

Chemical composition. All samples are rich in silica and alumina (at least 70% mass).

Mineralogy. All samples are rich in quartz-illite or quartz-kaolinite content.

Particle size. % of particles with d>45µm is <34% in all samples (ASTM C618).

Strength Activity Index. Mortars > 75% of the reference in all 750°C specimens at 28 days (ASTM C618).

Direct pozzolanicity. At least at one temperature for each sample material can be considered pozzolanic according to Frattini test.

Direct pozzolanicity. All samples show improved reactivity after calcination.

4.5.3 Significance of the findings in relation to explored literature and the research questions.

According to comparative studies on pozzolanicity or reviews such as [103], [108] mention that the outcomes regarding the pozzolanic activity of certain materials do not always correlate to each other in a linear manner and depend on the test procedures and conditions of each method. Therefore, the general practice is to support/confirm the testing using direct methods such as the ones used in this research.

On the material aspect of the samples studied in CO2REDRES, the key chemical and mineralogical properties that influenced the selection of potential cement substitutes in the Greater Region, and related to the samples that presented highest reactivity rates are the amount of silica and alumina and the presence of the amorphous phase post calcination. For example, two of the samples that presented pozzolanic reactivity already at 650°C through the SAI index, a test was run for a 550°C batch that did not return positive reactivity results, the SAI being comparable to the uncalcined sample and therefore indirectly confirming the hypothesized effects of calcination, i.e. the formation of amorphous phase and activation of the clay parcel at the range of 600 to 800°C.

As for the physical aspects, the results confirm that a fine material from the clay component creates a good substitute as it is similar to the range of cement (in the finer parcel). Drawing parallels of SCM with cement, the range of particle size of OPC and the shape of those plays a role in the hydration process and contributes towards the performance of cement [303]. Therefore, although the objective here is more the SCM analysis, it is interesting to understand better the mechanism related to particle size. In cement, particles smaller than 3 µm have a higher affinity for water and enhance 1-day compressive strength, while those in the 3 to 25 µm ranges contribute to 28-day strength. However, particles larger than 25 µm provide minimal contribution to compressive strength and primarily function as fillers [287]. Various of the final properties of fresh and hardened concrete such as slump, pore size distribution and packing density are influenced by particle size distribution of cement, and therefore also by all or any additions and substitutions made to the cementitious matrix. In the case of the studied SCM, on average the closer the particle size distribution was to a finer content, the better was the strength performance that can likely be explained due to resemblance of OPC.

As seen in the literature chapter, another physical attribute, the fineness of cement plays a role in determining its hydration rate and subsequent strength development. When cement particles are smaller, they exhibit a higher surface area relative to their volume, which provides more interface for water to interact with the cement. This increased contact accelerates the hydration reaction, leading to a quicker strength gain and a more rapid release of heat during the process. In essence, finer cement particles contribute to a faster and more energetic development of strength compared to coarser particles. This underscores the importance of the fineness of the SCM used so that it is similar to OPC and confirms that the fineness of the (clay based) SCM governs mechanical properties of blended cement alike [304]. As a reference from the samples studied, S7 characterized by the finest particle distribution and highest portlandite consumption, consistently achieves high SAI values across treatments, underlining the importance of particle fineness allied to reactive composition in driving superior pozzolanic activity.

Concerning the substitution rate, with the samples studied in this project, an increase beyond 20% was not systematically tested on all materials, but on one batch and the resulting SAI was lower which can possibly be explained by the increase of non-clay minerals in the matrix such as quartz that might have played a negative role beyond the optimal quantity. However, this is not a trend that can be conformed for all the materials studied.

Regarding the research question on the valorization potential of the studied (mostly clay-based) secondary waste materials as supplementary cementitious materials, the obtained results reveal a technical feasibility from the material technology point of view as discussed in this section. The data indicate that when these materials are properly processed—particularly through controlled calcination (often optimally between 650°C and 750°C)—they can exhibit effective pozzolanic properties, as demonstrated by their SAI values meeting or exceeding the minimum thresholds. The performance of these materials is closely linked to their mineralogical composition (such as kaolinite content), particle size distribution, and the extent of dehydroxylation achieved during thermal treatment. Therefore, with optimized processing conditions ensuring consistent quality and reactivity, these and similar secondary wastes have strong potential to be used as SCM, contributing both to waste reduction and to a more sustainable, circular construction industry. The challenges remain in providing consistently homogeneous materials in large quantities that can create an input for production that justifies industrial scale investments in current business models, The findings suggest a potential for scaling up the use of clay-based secondary waste materials as SCM in industrial cement production and developing reliable supply chains for these secondary wastes and integrating the processing steps into existing cement manufacturing infrastructure.

Overall, these findings indicate that with appropriate technological and operational adjustments, clay-based secondary waste materials can be effectively scaled up as SCM, contributing to a more sustainable and circular cement production process, while in parallel further long-term properties are studied to ensure their feasibility beyond non-structural elements.

4.5.4 Challenges and limitations

Certain difficulties might arise from the nature of the materials studied. Waste materials often exhibit variability in composition and physical properties, which can complicate thermal treatment and other processing methods necessary to optimize their pozzolanic activity. Moreover, ensuring a consistent supply of quality waste material is challenging, as waste streams can vary significantly by source and region. This variability affects the scalability and reproducibility of the desired cementitious properties when integrated into cement or concrete mixtures.

On top of the aforementioned challenges, certain limitations of the current experimental setup can exist since they were conducted under strictly controlled laboratory conditions, which may not fully capture the variability of field environments, such as fluctuating temperatures, humidity levels, and other weathering effects. While the lab-scale results are promising, additional research is required to validate performance, durability, and long-term behavior of these materials in real-world structural applications which leads into future research opportunities.

4.5.5 Further research opportunities

Future studies could examine the long-term durability and behavior of cement blends incorporating SCM under a variety of environmental conditions, including extreme climates and aggressive chemical exposures. The research could evaluate aspects such as resistance to sulfate attack, freeze-thaw cycles, carbonation, and chloride penetration, ensuring that these materials can meet or exceed the performance of conventional binders over the life cycle.

Another important aspect is the possibility of moving beyond laboratory-scale experiments. There is a strong need to implement pilot projects that integrate these SCMs into actual cement production and construction processes. In pragmatic ways that can show their potential. Field trials and demonstration projects can provide critical insights into processing scalability, supply chain logistics, quality control, and overall economic feasibility as well. Such real-world applications will help validate laboratory findings and facilitate the broader adoption of circular solutions in the built environment and cement industry.

Part III | Research methodology and data analysis of project CO2REDSAP

This page intentionally left blank

5 Methodology CO2REDSAP

5.1 Explanation of research approach and design.

The use of qualitative research methods in engineering research provides complementary and unique scientific insights that capture the complex dynamics of systems for which classic quantitative methods can only fit positivistic research design frameworks [305].

While enabling new findings, qualitative research can enhance engineering design research by offering a holistic view of interdisciplinary interactions in complex system design through multi-method approaches as shown in the study by Reis *et al* [306].

Another aspect of choosing multi-method research and adding qualitative research in engineering is its complementarity. While quantitative empirical approaches answer some of the research questions raised, they can't go much beyond the positivist objectivity into fields that cannot be observed in the laboratory.

In this thesis, the methodology for qualitative research is built upon the following set of components presented by Creswell in his book: Qualitative Inquiry & Research Design [307] as shown in the next figure (Figure 75).

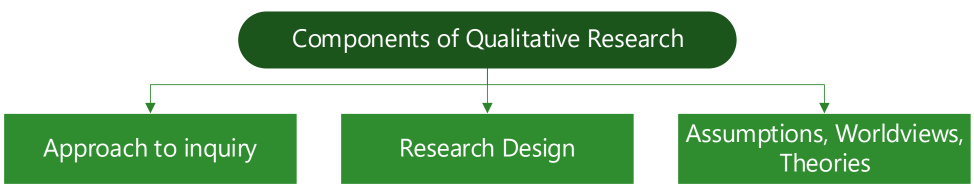


Figure 75. Visual of the three components of qualitative research – adapted [307]

The approaches of qualitative inquiry contain the components of the design process such as the interpretive framework, data collections and analysis, and the research questions, etc.

The importance of choosing a framework is to weave together different elements that are central to the discussion of the project or research and define a theoretical paradigm through philosophical beliefs and perspectives before diving into research strategies and methods of collection and analysis as subsequent phases. In Table 22, the chosen interpretive framework is presented, and its corresponding philosophical beliefs explained therein.

Table 22. Pragmatism as an Interpretive Framework and its associated philosophical beliefs – adapted [307]

Interpretive framework	*Ontological Beliefs*	*Epistemological Beliefs*	*Axiological Beliefs*	*Methodological Beliefs*
Social science theory that frames the theoretical lens in a study	*Describes the nature of reality as seen through certain lenses.*	*Describes how reality is known and what counts as knowledge*	*Describes what the role of values is and what biases are present*	*Describes what the process of research is i.e., the approach to inquiry*
Pragmatism	Reality is what is useful, practical, and "works".	Reality is known through using many tools of research that reflect objective (deductive) and subjective (inductive) evidence.	Values are discussed because of the way that knowledge reflects both the researcher's and participants' views.	The research process involves mixed methods i.e., both quantitative and qualitative approaches to data collection and / or analysis.

The choice of this framework does not imply that this research is not influenced by others, and in fact certain aspects of other frameworks such as transformative or postmodern in which knowledge is not viewed as neutral and is believed to reflect the power and social relationships within society applies to this chosen approach as well. However, the closest fit is the pragmatist framework since the research questions are rooted in practicalities of CE in the built environment and build on the previous quantitative approaches of project CO2RDRES, therefore using a mixed-methods approach overall.

Transitioning from quantitative research methodologies in an engineering perspective, it seems natural to focus more on the problem that is being studied while conducting qualitative research rather than focusing exclusively on the methods, which perfectly fits the pragmatist approach.

Moreover, the pragmatist approach is considered holistic in a sense that it views knowledge as interconnected and contextual in the broader context of inquiry [308]. This aspect gives even better means and perspective to understand the problem of circularity in the BE by avoiding discipline boxed linear solutions to complex phenomena.

Adding to the view of empiricism in science, pragmatism extends the tools and instruments of scientific inquiry all while acknowledging that reality is not absolute and must be relativized to the interaction between the world and the human beings who investigate it [309].

In the realm of scientific inquiry into real-world phenomena, the utilization of tools and instruments is necessary for advancing knowledge. These tools are vital to scientific progress, often exerting a significant and even decisive influence on the trajectory of research [310]. According to Ravetz, these tools must possess the capacity to grapple with complexity and variability inherent in the natural world. Moreover, their utility extends far beyond the specific problems for which they were initially devised. In essence, a well-crafted tool has a life and the ability to evolve, facilitating its extension to a broader array of problems and objects beyond its original conception.

5.2 Description of data collection methods and instruments.

The main data collecting instrument for this part of the research were interviews. The interview design started by defining the topics of interest to answer the research questions and is described in this section.

5.2.1 Interview design

This section discusses the content of the interview questionnaire, its structure, and other essential consideration and decisions taken at this phase of the study supported by the relevant references.

5.2.1.1 Content

The content of the semi-structured interview is centered around one topic which is circularity in the built environment and composed of 5 specific sub-topics T1 to T5 (Figure 76). Each topic contains a set of open-ended questions that form the basis of the discussion and starts with an introductory question that has the role of leading the conversation in a way that is comfortable to the interviewee and then delves into more challenging aspects as the interview advances.

Each of the topics is explored on three different levels L1 to L3 representing the positivist materialist view, the social constructivist view, and the pragmatist view of circularity respectively. These views are not intended to lead the interviewee or represent strict bases for analysis but are just part of the many different views that can be encountered in the discourse and content provided while discussing the topics and can serve as a thermometer on the views of circularity that each participant brings into the conversation, and in the discussion of the results thereafter.

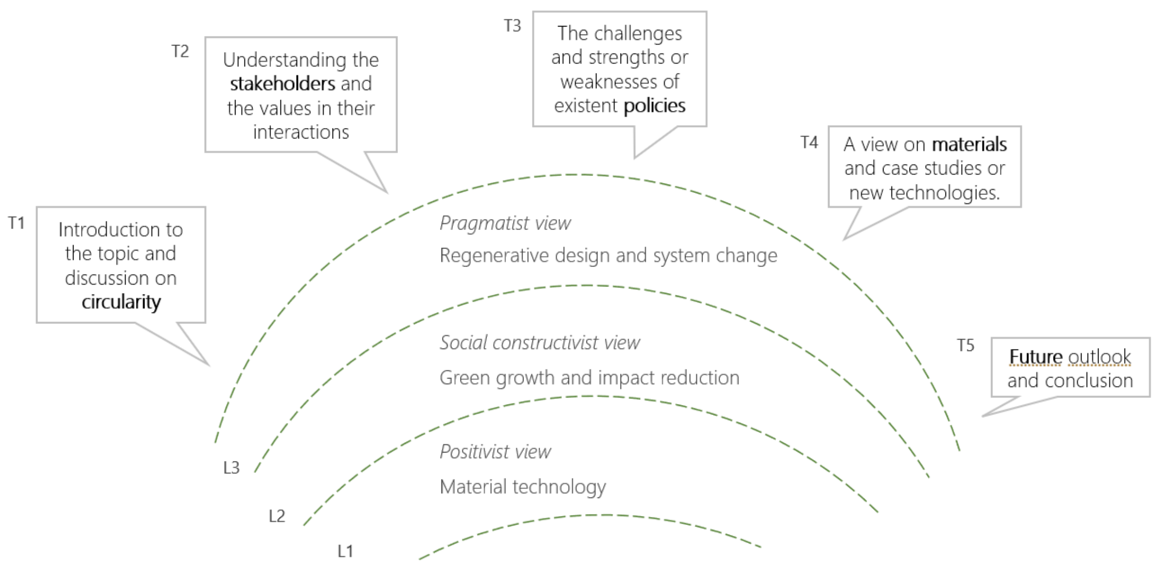


Figure 76. Diagram of topics and layers of the conceptual framework skeleton of the interview design.

The CE in the built environment would take different shapes depending on the ontological perspective (positivist, social constructivist, or pragmatist) through which it is viewed. A positivist approach would focus on measurable outcomes and standardized methods for circularity. A social constructivist approach would prioritize culturally specific circular solutions. A pragmatist approach would focus on practical strategies that work in real-world contexts, adjusting them based on continuous feedback in a systemic manner. Table 23 defines each of those concepts in more detail with the description of CE definitions, the focus area, and the processes that are related to each of the ontologies.

Table 23. Defining circular economy concept and approaches for each considered ontology.

Ontology	*Description of CE*[3]	*Focus area*	*Process, approach and tools.*
Positivist	An objective system with closed loops that can be measured and quantified scientifically.	Quantifiable metrics such as energy efficiency, waste reduction, material reuse, and carbon emissions, universal solutions.	Data-driven design, life-cycle analysis, standardization, Building Information Modeling, environmental key performance indicators, and certifications.
Social constructivist	A concept shaped by societal values under the ideal of sustainability where multiple solutions are possible.	Community, specific place-based understandings of circularity, environmental and social contexts.	Building practices shaped by local context, social dialogue, stakeholder engagement, and adding a social element to circularity.
Pragmatist	A flexible approach focused on practical outcomes with an emphasis on what works well in a specific context and that values interaction, and experience.	Real-world applications of circular economy principles based on feedback and experimentation.	Combination of methods and tools that work best for each context, hybrid solutions, innovation, best practices and adaptable design, replication of successful pilot projects, constant evaluation, and evolution of strategies.

5.2.1.2 Structure: weaving form and content together

According to Brinkmann, in his book on qualitative interviewing [311] there is a common distinction between structured, semi structured, and unstructured interviews. However, he upholds the idea that the structure should be thought of as a continuum ranging from relatively structured to relatively unstructured formats. Avoiding structure is generally not possible since even the most unstructured interviews have a central theme and at least one question to begin with, and having a totally structured interview might end up with a plastered outcome that is insensitive to what is present beyond the walls of the questions [311].

The choice of this format was made to ensure that the structure does not restrict or constrain the interview interaction [312], to allow flexibility for following up on any angles that come up and are deemed valuable [311], and to further give the freedom to probe and clarify without rigidity allowing the incorporation of knowledge from the diverse interviewee backgrounds [313].

---

[3] Concept definitions inspired from the theoretical literature on research philosophies by Creswell [307], Saunders *et. al* [346] previously cited in the text, and the idea of ontologies that tie to conceptual systems that give structure to thoughts and reality and that are not fixed objective structures but rather grounded in the worldly interactions by *Lakoff and Johnson* (in this case for example how stakeholders understand and interact with concepts of circularity), thus diverging from the ideas of traditional ontology in philosophy.

Despite the popularity of this data collection method among researchers and it being the most familiar strategy for the collection of qualitative data [314], only a few authors offer methods for designing semi-structured interviews, and many of these are overly intricate, lacking user-friendly simplicity due to excessive detail [315]. In a methodological review study performed by Kallio *et. al*, the authors analyzed several papers to arrive to a five-point framework for the development of a qualitative semi-structured interview guide which was used as a base for this research. The outline consists of the following steps:

1. *Identifying the prerequisites to use a semi-structured interview.*

   This first point relates to the basic question of knowing whether the study purpose can be achieved, and the research questions answered by this method of research.
2. *Retrieving and using previous knowledge.*

   The choice of the sub-topics that are linked to the thematic blocks of the questionnaire, as well as the questions themselves were based on an initial literature review that is presented in section 2.2 that led to the conclusion that part of the challenge in adopting circularity in the BE is related to stakeholders and policy in general.

   The discussion on materials is related to the findings of section 4 and the discussion on the future of construction materials.

   The final section with conclusions is an invitation to connect with the vision and expectations of interviewees as experts on the subject and is therefore not based on any literature study.
3. *Formulating the preliminary semi-structured interview guide.*

   After concluding step 2 and establishing the main topics to be addressed in the interview, the next step was to formulate the questions. For this part, keywords were extracted for each topic, serving as a central focal point for constructing questions. Initially, the plan was to create five questions to each of the five topics described in section 5.2.1.1. However, with further refinement to ensure the interview remained within a realistic time frame of 1.0 to 1.5 hours of conversation, some questions were merged. The final outline is presented in Table 24. Interview guide design: keyword per question per topic.

Table 24. Interview guide design: keyword per question per topic.

Topic	No. of questions	Keyword spectrum per question for each topic				
T1. Circularity	4	Definition	Standard	Goals /SWOT	Outliers	-
T2. Stakeholders	5	Identification	Links/ Relationships	Interests/ Objectives/ Conflicts	Challenges	Views
T3. Policy	5	Identification	Goals/ Transformation	Barriers/ Challenges	Measurement	Cases
T4. Material practices	3	Concept	Challenges	Solutions	-	-
T5. Future outlook	3	Conclusion	Future of BE	Transition	-	-

4. *Pilot testing the interview guide.*
   The aim of this phase is to confirm pashes 1 to 3 and the coverage of the questionnaire for the mapped topics as well as its relevance [315]. Please see section *5.2.1.5* for details.
5. *Presenting the complete semi-structured interview guide.*
   Subsequently to phases 3 and 4, the interview questionnaire was finalized and considered the logical guide that would set the direction and allow later for data collection from the interaction with the interviewees.
   Finally, it is important to note that during all those steps, other doctoral researchers who also work with interview data collection as a research method were also consulted in an informal setting on good practices and their views on structure, form, and content.

5.2.1.3 Mode

The interview modes are basic distinctions made by authors to characterize how an interview is carried out. In this research process, the interviews were all synchronous, spoken, and in person. Two interviews were held online through video conference.

5.2.1.4 Participants

The interviewees were chosen based on their expertise around either sustainability and environmental science and/or circular economy and the built environment. The sample size in qualitative research is often small ranging from 12 to 15 typically in homogeneous populations [316], so ensuring the adequacy of the sample size was important. In another study, *Kaiser et. al* [317], researched sample sizes for saturation in qualitative research confirming that saturation can be achieved with relatively small sample sizes. It was found that 9–17 interviews in a relatively homogenous study population often reached saturation.

The initial proposal was to have at least 3 and at most 5 participants from each of the three fields: public administration, private sector, and research and academia. In total more than 20 people were invited to take part in the research interviews as contributors and 12 accepted the invitation. The data was anonymized to ensure that the identities of participants are not disclosed. The end configuration of participants is described in Table 25.

Table 25. Participants of the qualitative interviews presented by sector and field of expertise.

Participant ID	Sector	Field	Country
A1	Public Administration	Environment	LU
B1	Public Administration	Sustainability	LU
C1	Public Administration	Sustainability	LU
D1	Public Administration	Construction	LU
A2	Research and/or Academia	Engineering	LU
B2	Research and/or Academia	Circularity	LU
C2	Research and/or Academia	Urban studies	LU
D2	Research and/or Academia	Architecture	LU
A3	Private Companies	Construction	LU
B3	Private Companies	Consultancy	LU
C3	Private Companies	Design	LU
D3	Private Companies	Industry	LU

5.2.1.5 Pilot interview

Authors often describe multiple benefits of conducting pilot interviews [315], [318], [319]. In this project it was used as an instrument that would identify eventual flaws in the interview guide and allow for enhancing its validity and reliability [319] by adaptation of the questions and style to fit the target participants. Another advantage of having pilot interviews is the usefulness as a training exercise that helped increase the overall confidence in conducting synchronous qualitative research interviews [318]. Finally, the feedback obtained from pilot testing aided in the systematic refinement of the interview questionnaire and contributed towards its objective development [315].

Two non-recorded pilot interviews were carried out before the starting of all other interviews to get a sense of how the interview structure works and what the interviewees thought about the questionnaire. A total of three people participated in the two interviews, and they were all posteriorly interviewed with the final questionnaire. None of the pilot interviews were recorded.

5.3 Data analysis techniques and procedures.

Data analysis in qualitative research can use a variety of different techniques including mainly content analysis, thematic analysis, narrative analysis, discourse analysis and grounded theory [320]. One of the common factors among these techniques is the coding process of data into thematic categories by means of identifying, classifying, and organizing the data into codes.

A software program (MAXQDA) designed for computer assisted qualitative methods was chosen for organizing, coding, and storing the collected data. The data collected in the interviews in form of audio files was transcribed manually by listening to the interviews and adjusting the generated text from the recording/meeting platform WEBEX hosted on the university servers.

For the purpose of generally performing content analysis without looking deeply at other nuances that might be present in the data, the flexible interpretive approach of grounded theory developed by Charmaz [39] was used to code and analyze the data and answer the research questions laid out at the beginning. When compared to other types of grounded theory research frameworks, this approach permits a more adaptable and less structured way for data analysis given its flexibility [320]. In her book Constructing Grounded Theory, Charmaz backs the idea that researchers can adopt and adapt the otherwise rigid guidelines to conduct diverse studies that fit their needs using twenty-first century methodological assumptions and approaches[39].

5.3.1 Grounded Theory and the research data

Grounded theory methods first emerged from the work of sociologists Barney G. Glaser and Anslem L. Strauss when they developed systematic methodological strategies for their research that were then adopted and used by social scientists for studying various other topics [39]. It stemmed from the need to advance beyond the positivist concepts of seeing knowledge as derived from empirical evidence and strictly measurable scientific methods while ignoring human problems and research questions that did not fit positivistic research designs that overemphasized quantification and neglected a holistic view of science. Despite the fact that grounded theory came to give structure and rigor to qualitative research based on the merging of two contrasting schools of thought: the Columbia University positivism, and the Chicago school pragmatism brought by Glaser and Strauss respectively, it still diverged as time passed by and each of its founders went into a separate direction.

Since the data is often connected to the nature of the investigated subject, and the research questions seek to make sense out of it rather than prove or disprove a certain idea or theory [39], the grounded theory choice made sense to use as a research method in order to discover the emerging patterns in data and value the individual insights of the contributors in the research context. The idea is that the outcomes of this research are not coming with a theory off the shelve, but rather one that is grounded in the data obtained from the participants, and that generates a general explanation of a process through the views of those participants [320].

The choice of grounded theory among all the possible methods of qualitative research stemmed from its flexibility of not being restricted to one field of social science [39], its ability to reveal social relationships and connections of groups in a way that facilitates the development of new theoretical insights [321], especially in the case of stakeholder analysis and connections which are part of this study, and their connection to circularity in the built environment, and finally it being a qualitative research method that utilizes actual data gathered to identify, develop, and integrate concepts, applicable to various professions.[322]

Although grounded theory is deeply connected with field work and field data collection, it is still suitable to apply its principles using less observation extensive, and field placed methods of data collection, such as the expert interviews conducted for this research.

Of the other defining features of grounded theory, the focus on a process that has phases and movement over time as defined by Creswell [320] fits into the object of this study which looks at how the construction ecosystem in Luxembourg represented by its stakeholders influences the adoption of circular practices in the built environment which is not a static system.

Another defining feature that is considered in this methodology is the continuous data collection that revisits the interviews and the ideas generated from those considering new insights and input from new interviews, so that gaps are filled along the way [320].

5.3.2 Coding through the data

The choice of grounded theory as a method impacts more the data analysis than any other part of the research. To analyze the data, it has to be organized in a certain way, i.e. coded to reveal it content. Coding involves categorizing sections of data with concise labels that both summarize and represent each data segment. These codes demonstrate how you choose, distinguish, and organize the data to start an analytical interpretation of it [39]. In its simplest way, coding is defining what the data means.

5.3.2.1 Initial coding

This phase is meant to be an introduction to the gathered data. The coding in this study started with one-to-two-word simple codes that did not follow a certain structure, once simultaneously with the transcription process while listening to the recorded interview and doing the memo writing, and a second time after the end of the transcription while rereading the interview record to realize if some important idea has been left out. This provided the initial simple and short coding, that was extremely valuable for the subsequent coding phase to make analytic sense of the material at hand.

5.3.2.2 Focused coding

The objective of focused coding is to get involved and learn from the data, all while making sense of it, connecting the different interviews together to get a bigger picture, and making discoveries and getting a better understanding of the code and the data together [39].

It builds up on the codes that were assigned before in the initial coding phase and would merge some and delete or substitute others as the iterative process went on. To best illustrate the process, an example of the transformation of initial codes by grouping is presented in Table 26.

Table 26. Sample evolution of initial code segments into final code in different interview texts.

Interview text	Initial codes	Final code	Observation
...due to the awareness and the socioeconomical and also material resource. How we get resources and how is it used? People are getting more aware of it. There is a scarcity of building materials. (Transcript A1, Pos. 21)	awareness scarcity / material shortage	opportunity for circularity	All the initial codes refer to different elements: *awareness*, *scarcity*, *uncertainty*, *climate change*, and *financial levers*. Some are clear and others are less so. For instance, *uncertainty* can mean so many things and yet not be related to what the interview section conveys. *Scarcity* as a standalone code without the context could perfectly have a negative association. However, the common idea among all those initial codes is that the represent opportunities for a transformative shift from linear to circular concepts in the construction industry, therefore an umbrella code "*opportunity for circularity*" is a better fit.
At the construction industry per se, there are mega trends of challenges ahead of us. One is really the impact of climate change on the built environment. We are ignoring that for the moment, but that's a big challenge. (Transcript C3, Pos. 91)	uncertainty climate change	opportunity for circularity	
...because we've got also the financial possibility to do this kind of building (Transcript A2, Pos. 19)	financial lever	opportunity for circularity	

5.3.2.3 Code saturation

Saturation can be defined as a point in the analysis at which no new insights are revealed from the data, or a stage at which the data analysis process identifies recurrent themes and codes not revealing any new information [323]. As described previously, the saturation point was taken during focused coding when no new ideas emerged from the interviews, and all similar codes have been grouped.

5.3.2.4 Memo writing

Although memo writing is presented as the next stage after the saturation of coding according to the grounded theory method proposed by Charmaz [39], not every string of information was memoed in this research primarily due to two reasons: (1) some of the text and code being obvious and ready to be carried into the analysis as they are, and (2) the fact that there is no field observation element since the interviews were done with experts in a fairly static environment where interactions between third party people or actions were not present or observed and thus no further input through memo creation would enrich the analysis later on.

In the example presented in Table 27, the necessity of writing a memo can be seen as the idea expressed by the interviewee in this segment has a wider implication on the research findings and is embedded in a phenomenon that transcends just that sentence or its direct meaning, comparing two types of companies with two different approaches to adopting circular strategies.

Table 27. Example of memo writing in a coded text segment

Situational Circularity / Circularness The idea that the same industrial actors might have different takes dependng on where they are in the value chain. If they are on the further edge and they do not benefit from circular practices (e.g. would sell less, or there is no added value to pass on to the price, etc.) they might support it less than someone who would benefit from it financially. This is one of the costs of implementing circular strategies in an economic system that is centered on profit only. It always has to be profitable to everyone along the chain, otherwise it risks being sidelined. This relates a lot into stakeholders and how they act and interact in ways that promote circularity or stall it. Interview text segment	Associated memo
…I see maybe construction companies are more open towards this because they are maybe further down the value chain, so for them maybe a circular economy where they have greater access to materials can bring more benefits in having more options? While maybe manufacturers would see this more as a threat where they might not be able to sell as much product as they used to… *(Transcript B1, Pos. 42)*	

5.4 Ethical considerations.

The research protocol was reviewed and approved by the ethics committee of the university of Luxembourg in August 2023, ensuring adherence to all relevant ethical guidelines and codes of conduct.

Participants in the research signed consent forms to authorize the recording of the interviews and were given information sheets on the project and the data handling procedures, as well as their options in the future should they want to remove their data.

The primary privacy concern in this project is ensuring the protection of individuals from being identified or linked to any data regarding their behavior or personal opinions shared during their contributions. Any data collection, processing, and storage were and are subject to strict security measures to safeguard personal information. Participants were assigned unique identifiers, which were not connected to their names or any personal details. These identifiers were generated using alfa numerical combinations based on the sector of action of each participant. Any information provided by users that could potentially reveal their identity were promptly removed from the transcribed texts.

This research complies with the University of Luxembourg's data protection regulations.

5.5 Critical reflection on self and research merits and limitations

While a research project provides answers to certain questions using certain tools and methodologies of inquiry, it also comes with its merits and limitations, especially due to the human factor involved, and a reflection process on those elements could help understand the strengths and weaknesses of the research and acknowledge personal assumptions, beliefs, and even potential bias.

As a starting point, the researcher would take a step back and look at himself and the agency associated to the quality of scientist or researcher while doing his research. Earlier in this chapter an interpretive framework, a sequence of data collection, and then data analysis have been described. At a first glance, all the choices taken seem to be perfectly appropriate from a scientific perspective and well founded in the relevant literature. However, if we think how reality shapes science and therefore research, one can't ignore how one's personal reality and identity shaped and continues to shape one's worldviews, neither can one overlook how the changes around us in the world reshape how one think at every interaction and make us revisit these views quite regularly. The ideas and assumptions with which this research started are not the same as the ones it ended with. This section develops a critical stance on the position as a researcher, the research journey, the methodology, the interaction with participants, and the impact of this research. *The rest of this section is written in first person due to its personal nature*.

5.5.1 Position as a researcher

As a starting point of this reflective process, I would like to borrow a concept from Brazilian philosopher Ribeiro [324] in her book *Lugar de Fala* which translates into English as the *place of speech* or *standpoint* – a concept from sociopolitical studies that states that each one of us has a unique social locus which defines what we are able to say and how what we say is perceived by others. Although this concept is originally associated with giving a credible and independent voice to marginalized communities and is also related to and influenced by previous thinkers such as Foucault [325] who discusses the power relationships present in different types of discourse, and the position occupied by the speaker in the power dynamics in his work, I would still adapt it to the critical thinking of my researcher position.

As a PhD candidate in a western university educational context with a mix of other non-European influences in my previous education, my personal experiences shape part of my values and drive my reflexivity in research. As much as I found myself dissociated from subjectivity in the first part of my work while performing rigorous experimental research based on rigid and standardized procedures linked to a positivist view of science and knowledge and with little room for any sort of personal bias, in the second part of the research I realized that my choices have become wider than those offered by a set of standards and rules, since they depended on my capacity as a researcher to develop them and to ask the right questions, and with this came the uncertainty of working with interview questions that albeit based on solid literature and previous results of other researchers, still had to be formulated without an engineering standardized testing method guiding every step of the way. There is where I bring my own and the participants' experiences and perspectives into this study with assumptions that end up infusing the research with a personal touch no matter how objective one seeks to be. I see awareness as an essential part for a transition into a sustainable world where collective action is not only necessary but indispensable - no one does anything alone, and no one does anything if they don't know what they're doing. Therefore, the focus on collective effort and awareness and acknowledgement of the problems we face was a present element in this research. Throughout the process I questioned myself many times if I was looking at the problem just for solutions, like we usually do when we are obsessed with the scientific method alone, and with the passage of time I got to think that maybe solving a problem at 100% is not the final objective but rather trying to reframe it, understand it, react to it, or simply look at it from a different perspective is already a great way towards the solution that often times is not a unique and punctual action, especially in complex systems with multiple input and feedback loops involved as is the case for the construction field and industry. The solution to a just sustainable transition in the construction industry lies beyond coherent policy changes or stakeholder alignment in my view, but very likely goes through these and many other aspects beyond, as miraculous solutions are rarely the answer although they are highly sought after.

When I look at circularity I do not see it as a merely positive or negative aspect of sustainable transitions in the built environment, but I regard it as a solution element to some extent with the potential of embodying a lot more meaning than technocentric approaches, probably because of my understanding of circular practices as something the is beyond closing a loop and more directed into a path of design for regeneration and reworking the relationship that humans have with the built environment as an ecosystem that groups different forms of life and structures. Herein came the part on looking to understand how our perception of reality and philosophical background as experts and scientists influences our view of circularity. I believe in a biocentric approach in which the nature of everything is interdependent like in the multispecies sustainability concept [326] where reductionism is not the solution.

In sustainability science research, the importance of critically engaging with knowledge cannot be overstated. Drawing on Derrida's concept of deconstructionism [325], it becomes apparent that all knowledge and constructions are inherently *contingent and partial* – even the knowledge that informs research. Deconstruction offers a lens to unsettle existing institutions and disciplines, not to discard them, but in a way to explore what systematically escapes their frameworks. According to his theory, by disturbing already established knowledge, we open spaces to examine the tensions, loose threads, and subtle openings that traditional structures often overlook. This practice aligns with Spivak's interpretation [325] of Derrida's notion of dismantling in order to reconstitute—breaking down existing paradigms not simply to abandon them, but to rebuild them in more inclusive and nuanced ways, i.e. taking what works and making it work better in a pragmatic way, hence an interdisciplinary approach to research.

In this light, the concept of *trace*, from French which denotes the "absent presence" of meanings and imprints on our words before we even articulate them, becomes particularly relevant. It compels me to reflect on my understanding of circularity within the broader discourse of sustainability: Is circularity merely a means to achieve sustainability, or is it an end in itself? These questions shape not only the theoretical framing of my research but also the very practical aspects, such as designing interview questions. It makes me reflect if my questions already hold a meaning and an answer, and if my framing is influenced by the meanings I bring as a researcher. Here, by approaching knowledge with a willingness to explore its contingencies and absences and be aware of my imprints on the research, I aim to uncover new pathways for interdisciplinary inquiry in engineering, by working on ontological meanings and contributing to the dynamic and evolving field of sustainability science.

5.5.2 The research journey

The research journey started with a strictly quantitative approach that is easy to control and predict, however as it shifted into the inquiry on aspects that are beyond the laboratory element it became a process of discovery but also one of self-reflection and influence as mentioned earlier. As a researcher, I shape the direction of my study through my choices—what questions I ask, what methods I use, and how I interpret findings. My perspectives and experiences from the very beginning of this research, and even the exchanges with experts whom I did not interview in the research process, inform the framing of the problem and the analyzing of the data. At the same time, the research itself shapes me, refining my critical thinking and deepening my understanding of the subject. By remaining reflexive, I strive to be aware of my role in co-constructing knowledge, ensuring that my interpretations remain grounded in both rigor and openness. As Charmaz puts it in her book on grounded theory "*My approach explicitly assumes that any theoretical rendering offers an interpretive portrayal of the studied world, not an exact picture of it*" [39].

5.5.3 The methodology

With a background in engineering and a focus on sustainability in my education, my academic training shapes my approach to studying circular economy practices. My knowledge in these fields naturally informs the questions I ask and the way I analyze data. However, the recent infusion of social science through the interdisciplinary nature of this thesis gave me much more input to work with. I learned want is qualitative research and how to couple it with quantitative outcomes despite it being quite rare in engineering studies.

The choice of semi-structured interview method is probably one example of the mix of backgrounds that pushed me to want to understand research questions further than the limits imposed but still structure them in a way, therefore, not going for a fully structured neither an unstructured setting, to keep control of the subject matter while exploring at the same time the direction to where it takes the research.

5.5.4 The interaction with participants

Engaging with participants in my research has been both enlightening and transformative. Each interaction is a reminder that research is not just about data collection but about building meaningful connections and understanding diverse perspectives that one might not agree with personally but continue to acknowledge its validity as a point of view. In many ways, participants offered glimpses into new ways of thinking and reshaped my understanding of certain concepts challenging premade assumptions and deepening my insights. I have learned to navigate the balance between being an interviewer and an active listener, ensuring that their voices are authentically represented. This reflexivity practice throughout this section allowed me to approach my research with greater empathy, adaptability, and a commitment to ethical engagement.

5.5.5 The impact of this research

As I navigate my research on circularity in the built environment, I find myself continuously questioning the role of science in shaping a more sustainable and just future. Science, rooted in positivist traditions, often seeks objective truths, yet the complexity of sustainable transitions demands a more nuanced, reflexive approach—one that embraces human subjectivity and the interconnected social, political, and economic forces at play. I recognize that circularity is not just a technical solution but a contested space of opportunities and limitations, shaped by competing interests, barriers, and systemic constraints. My work aims to highlight these tensions while also considering the power of ontology in framing sustainability narratives, influencing how problems and solutions are constructed. This awareness challenges me to be intentional in my language and critical of dominant scientific paradigms that may overestimate their capacity to drive change.

Moreover, the transition toward circularity cannot happen in isolation; it requires multi-stakeholder engagement and coherent policies that consider systemic action. Circularity in the built environment involves a wide network of actors—policy-makers, businesses, designers, urban planners, and local communities, among others —all of whom bring different perspectives and priorities to the table. In my view, without a framework that fosters collaboration and aligns incentives, circular initiatives risk being fragmented or ineffective. A systemic approach ensures that circular strategies are not merely technical fixes but are embedded in structures that address broader sustainability and social justice concerns. Coherent policy must bridge disciplinary silos, integrate long-term thinking, and create regulatory conditions that enable innovation while preventing superficial sustainability claims.

Additionally, after having done the interviews, I further reflect on whether circularity should be seen as an end goal or merely a step toward a more regenerative, sustainable future. While circular strategies are often positioned as inherently positive, I should remain critical of their real impact, ensuring that they serve as meaningful actions rather than rhetorical commitments. Through this reflexivity, I aim to contribute not only to the discourse on circularity but also to the broader reimagining of built environments beyond material science and SCMs that are just, adaptable, and genuinely transformative for a better life on the planet.

This page intentionally left blank

6 Data Presentation and Analysis CO2REDSAP

6.1 Presentation of research findings.

The interview data analysis was centered around the topics T1 to T5 presented in the methodology section to allow a meticulous understanding of the landscape of circularity in the built environment in Luxembourg from the conceptual, stakeholder and policy points of view all while connecting this to the material question from the first part of the thesis in project CO2REDRES. Through a thorough investigation to be presented in this chapter, the findings shed light on the synergies and gaps within the current stakeholder landscape, discussing circularity, and offering valuable insights for policymakers, industry stakeholders, and researchers as well as involved citizens, with a dedicated effort to fostering a new idea of sustainability beyond the carbon emission fixation and material efficiency in current and future urban developments.

This chapter is divided into two parts. In the first the data analysis outcomes are presented and in the second the ensemble of these results is discussed in the research context.

6.1.1 Data analysis

This section folds into the five main topics of the interview framework presented in Figure 76 in section 5.2.1 and in each subsection answers different parts of the research questions raised in the beginning of this thesis in section 1.4 of chapter 1.

6.1.1.1 Circularity in the built environment

This section answers research questions g, i, j, and l.

6.1.1.1.1 The understanding of circularity through the individual lenses of participants

Circling back to project CO2REDRES to start the analysis, the main contribution aspects towards sustainability in the built environment were linked to material circularity. The reduction and elimination of quarry and industry waste and by-products by valorizing them, the reduction of emissions by substituting OPC with SCMs, and the protection of nature and biodiversity by avoiding landfilling of these same secondary products and the extraction of more raw materials for OPC production, are all actions that can be traced to the big concept of circularity in the built environment. Therefore, comes in the importance of first discussing this concept and considering how its understanding by different experts in the field relates to the action that end up influencing the use of SCMs.

It is not a novelty that different people within the same field of expertise might have diverse views on some matters and agree on others. For this reason, the analysis began with the understanding of circularity as a way of discovering the views that each interviewee has on the topic, and how do these views compare to the peers from the same sector group and the other groups. The different definitions of circularity are presented in Table 28.

Table 28. Summary of the different understandings of circularity per group/sector.

Sector	Definitions of circularity (excerpts)	Consensus points among contributors	Divergence points among contributors
Public Administration	*A multilayered circle that is never perfectly closed (A1)* *Multiple circles feeding onto outputs from the imperfections of circularity (A1)* *A way of trying to reuse and extend life of structures and materials (B1)* *A system to organize stocks and flows of materials (C1)* *Doughnut concept of planetary boundaries can be applied to circularity (C1)* *Closing biological and technical cycles (C1)* *A mean to become more sustainable and not a goal in itself (D1)* *A system to exchange materials and money with a circular vision of keeping a pattern of flow in a closed loop (D1)*	(1) The technical definition of circularity and material flows inside a model that is intrinsically connected to technological innovation. (2) The views on the imperfections of circularity in practice, such as the impossibility of a perfectly closed loop circular model without flows that escape. (3) Circularity as one of the means towards a sustainable transition in the BE.	(1) Not everyone points to the social aspect of circularity or implies it should exist beyond the technical / biological sphere. (2) The view of circularity as a transformational catalyst for change is present but not a common denominator. (3) (3) The level of urgency for action is divergent among different contributors.
Research and Academia	*Considering the built environment as a material bank (A2)*	(1) The simplicity and comprehensibility of the concept as an easy to imagine and easy to deploy idea.	(1) The permanence of the concept: is it a passing by or a staying strategy?

	It is a question of flows and inputs and outputs of resources (A2) *Circular economy is a buzzword like others before and others that will come (B2)* *Two circles (technological and biological) concept that is simple to understand (B2)* *There are no endless circles. Materials cannot be recycled forever without any loss. (B2)* *The most frequently used definitions are quite comprehensive. However, too narrow and focusing on either technological aspects alone or are limited to single industry sectors or products. (C2)* *… how can we make our environment more resilient and more holistic and break this idea that everything is unlimited, so how to deal with the limits? (D2)*	(2) A clear sign that the current concepts are preoccupied with the technological aspects that leaves social and even certain basic environmental concerns behind. (3) A holistic approach beyond the economy itself which extends to other system actors and flows such as humans, other living beings and nature. (4) (4) The unanimous acknowledgement of a need to change the current way of constructing.	(5) (2) The decision of which actions and strategies are more important than others to apply circular strategies.
Private Companies	*Circularity is mainly focused on the materials that you really use for the building that you can reuse them afterwards. (A3)* *Another aspect is to bring in [from outside] reused secondary materials. (A3)* *Circularity is to close the loop. (B3)* *[Circularity] in construction is to think from the beginning, designing already to predict what's going to happen, that the building should be*	(1) The role and the importance of digitalization and data in circular economy. (2) Design thinking – circular strategies are design based. (3) Financial viability as an important part of circular strategies. Companies are still for-profit entities that need	(1) The R-strategies: non-alignment on the level of circularity of reuse and recycle actions. (2) The extent of the degree to which circular economy can be regenerative.

	disassembled, reusable in the end of the first life cycle and then keeping all the material, all the service, all the energy that you have spent in the beginning in the loop and then it doesn't go back to the nature. (B3) *The idea is to let the nature recover because we have already exploited a lot. (B3)* *In my experience circular economy is all about design. So, our main focus is really in the design not in the waste handling and I think we need the circular economy definition 2.0 without [incorporated] linear strategies such as reduce and recycle. (C3)* *to finish off my definition of circular economy, it's a systemic change. So, we need the system to change. It's not only the built environment that needs to change. (C3)*	to survive in the market.

What do these definitions reveal and how do they impact reality?

The importance of understanding how a definition impacts practice is because of the meaning that is attributed to objects, concepts, and interactions. Thus, if one were to consider how ontological beliefs about the nature of reality influence ideas and concepts, one understands that practices are ultimately shaped by the individual's or organization's understanding of a concept, and the ontological perspectives that surround it. Ontology matters in this context, as it influences meaning making, agency, and action through the various types of ideas and ideologies [327]. Now this might be a pressing question in some fields of research more than others, but it still is a valid question for all bodies of knowledge in science and specifically in research that deals with the dynamic topic of sustainability.

Moreover, moving beyond theoretical influence of definitions and illustrating it in practical reality, the dynamic relationship between design concepts and meaning making in a given context underscores the powerful role of objects and concepts in shaping and reflecting human values and experiences. Objects and concepts embody the meanings and values of their designers, and as we interpret and interact with these objects, we inevitably enact these embedded meanings and values. This process highlights the critical importance of definitions because they are statements of meanings. How a concept is understood and perceived directly influences practices and actions, shaped in part by the material world and our interactions with it, and in part by a system of beliefs and values. The extent to which values and meanings are embedded in objects around us is often underestimated, therefore not giving enough importance to how the ways we understand a concept impacts reality and action. It is not any different with the concept of circularity.

To be truly interdisciplinary and draw a parallel from engineering to social science through art theory, we can refer to the central concept in Ways of Seeing, a book by John Berger [328] that reads "*The way we see things is affected by what we know or what we believe*." This highlights Berger's idea that perception is not purely visual but also cognitive and interpretive which emphasizes the influence of context on perception. Therefore, the author defends the idea that the way we see things is influenced by a range of factors including context, cultural norms, and individual experiences and shaped by our knowledge and beliefs. This relates directly into how different people perceive circularity, which is a concept that beyond its basic understanding of looping materials and conserving resources, requires a reasonable amount of other complex input to achieve a more holistic definition.

In multiple occasions, albeit not while formally defining circularity, interviewers mentioned awareness, and part of it relates to the creation of such a state where the object of sustainability is defined and understood above all. *"I think it's missing the awareness of the people to really know that this is important because … sustainability … is still a concept that many people don't understand, or they understand in fractions or just parts. (B3)"* illustrates well this idea and furthermore supports the idea that the partial understanding of the concept is not enough, and that there are limitations related to a definitional quagmire as Corvellec *et al.* [171] put it.

This awareness might be triggered by multiple means, but the initial step almost always needs an external force that helps create an opportunity to plant the seeds of circularity or even other strategies. One interviewee in reference to global events involving exercises on the future of the built environment stated: "*These were two major events which raised our awareness about the paradigm that we had to change into something which goes into different way of dealing with the built environment. (D2)*"

In contrast to the prevailing assumption that everyone is onboard for a transition towards sustainability, there were also reflections on whether society is really prepared to change and wants to go through the process in first place. *"I mean this is a question, do we want to go through awareness, and do we want this kind of change? (B2)"* This implies that change has a price that not everyone is willing to pay. Complementarily, other interviewees see that people are aware of the need of a change but simply do not want to go through the trouble *"people want change but do not want to change (C3)"*

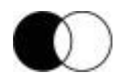
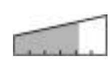
Throughout the gathering of the definitions and perceptions of circularity in the data, one common idea that is present among most interviewees across the three sectors i.e. academia, private sector, and public administration – is that design is an essential lever for circular economy. This concept matches the research findings of other studies as well [257], [329], [330] where systemic thinking and design principles can be used to evoke a fundamental change in approach towards sustainability if well used.

While this constitutes a promising pathway, several challenges remain especially in creating and adopting consistent circular economy practices across involved stakeholders and regulatory frameworks, which can create barriers to widespread adoption of circularity, and this will be discussed at length later in this section.

6.1.1.1.2 Circularity vs. sustainability

As the data presented previously shows, not everyone agrees on the limits of the definition of circularity and what it includes or excludes, and this tends to become more accentuated when the discussion on sustainability is introduced. However, there is a common perception among experts across the field of construction industry that future visions based on circular strategies represent favorable societal shifts regardless of if the interviewees see circularity as a means or an end itself in the transition towards sustainability. In their views it is favorable in absolute terms to have circular economy concepts embedded in the construction sector, albeit with different priorities. What can be concluded from the analysis of the different definitions is that despite the importance of the circular economy concept, the conceptual relationship with sustainability is not always clear, which comes at a detrimental cost to its implementation, and this is in line with the research as argued by *Geisdoerfer et al*. [331]. The researchers identified 8 different relationship types from a vast literature review in their study that illustrate the degree of connection between the two concepts: circularity and sustainability. Those relationships are shown in Table 29.

Table 29. Relationship types between the Circular Economy and sustainability [331].

General direction	Type of relationship	Short description Circularity/closed loop systems are seen as …	Graphical representation
Conditional	Conditional relation	One of the conditions for a sustainable system	A→B
	Strong conditional relation	The main solution for a transformation to a sustainable system	A➡B
	Necessary but not sufficient conditional relation	A necessary but not sufficient condition for a sustainable system	
Beneficial	Beneficial relationship	Beneficial in terms of sustainability, without referring to condition-ality or alternative approaches	+A→+B
	Subset relation (structured and unstructured)	One among several solutions for fostering a sustainable system	
	Degree relation	Yielding a degree of sustainability with other concepts being more and/or less sustainable	
Trade-off	Cost-benefit/trade-off relation	Having costs and benefits in regard to sustainability, which can also lead to negative outcomes	
	Selective relation	Fostering certain aspects of sustainability but lacking others	

After having initially defined circularity in the built environment for the different contributors, by looking at the nature of change expected and how much of it is related to a transition outcome towards sustainable practices or simply rooted in the technocratic view of circular economy, in the data analysis, under the code category *change for circularity*, two main ideas can be extracted: the first about what needs to change for circular strategies to advance, and the second about the relationship between circularity and sustainability. This second sense is implicit in the code since the change it refers to is a dynamic action and usually used in defining a motion of arriving towards a destination: sustainability in most cases.

Through looking in the interview for data the directions defined in Table 29, it showed clear signs that the more the relationship direction pointed towards the trade-off view, the less holistic the understanding of circularity became because it is fragmented and based on one or few standalone actions, for example the reduction of carbon emissions, or reducing waste, etc. In contrast, the more the relationship pointed towards a beneficial or conditional view the better were the chances towards a more comprehensive and symbiotic understanding that favored a more cohesive change strategy.

However, all experts understood very well design aspects of circularity in the built environment, but some fell short of systematically connecting it to a broader view that favors sustainability, for example the below excerpt:

"…there can be many goals that you can reach with circular economy even without focusing on the environment. (B1)" exemplifying a beneficial subset relation and indicating the possibility that some actors would use circularity as strategy for other means than sustainability.

Whereas others who still had the same view on circularity (beneficial subset) managed to connect it to one or more sustainability elements even through defying a negative outcome or a misuse of circular strategies, for example:

"And that's why it is so important to really understand that circular economy is all about strategies and at least a layer of purpose. Why are you using that strategy? Because you can use it as a hammer to kill competition, not to improve the overall environment. (C3)"

"There's not, there's never one solution. It's really a kind of a harmonious balance between optimums and it's really, yes, a question of how you define the objectives. (A2)"

The point is that when the view of circularity is not holistic, one or more important elements get left out. So there maybe needs to be a new definition such as regenerative circularity, instead of simply circular economy, that (1) expands the definition and understanding beyond the strict market/industry economy aspects, and (2) contributes to a better relationship with sustainability as a strategic way of achieving what it stands for, and not just one part of it. While the definition of economy does include many aspects beyond goods and services, in the basic understanding of circular economy, the external limit few go beyond seems to be the simple addition of the environmental aspect to the classic model. "…*circular economy is not circular ecology. It's all about economy. (C3)*"

6.1.1.1.3 Normative dimensions to circularity

Taking a leap from a descriptive dimension to a more normative dimension, an understanding of circularity stemming from norms, values, and standards that impact human behavior, can positively influence action by transmuting the discussion from "what is" to "what needs to be done" as stakeholder groups learn which circular models are practicable and how complex it would be to transition towards a regenerative circular future should we not create and adapt visions to achieve it.

Part of the normative aspect in the definitions can be visible through the connections made in reference to circular material flows within the circular loop, a pragmatic element of circularity that recognizes the question at hand all while thinking of the application and the design needed to get there. Understanding flows at all levels in the circular built environment is fundamental to push change in a certain direction, and this happens by studying the movement and exchange of resources, materials, energy, information, among other things. According to the interview data, this is one of the important and easy things to consider for a start – it is not only measurable and feasible, it gives a deep screenshot on the order of magnitude and helps in better understanding possible circular solutions that work "*because [it is] really a question of flow inputs and outputs, and it's large quantities of resources, mineral resources, metallic resources, organic resources. So, it's for me a kind of low hanging fruit to be considered, even though some of the actors or stakeholders are considering it complex.* (A2)"

In addition, apart from narrowing and closing the loop, understanding and tracking flows provides enhanced resilience to the built environment through allowing for adaptability in a system that can respond to changing conditions and eventual disruptions such as resource shortages or climate impacts even when it is not foreseen and planned, as well as reducing the dependency on global supply chains while choosing regional and local resource producers.

"We had COVID. That was an eye-opening event for the also for construction sector people, even the material was there they couldn't get it. So, people had to develop regional materials flows and streams in order to be self-sustaining. (A1)"

Another practical point that was raised was that through understanding flows better, we allow integrated urban planning that considers the interdependencies between different systems, such as energy, waste, water etc. and helps in optimizing energy use and minimizing energy loss. However, this can work as well for other systems.

"To a circular economy in construction, so you also start with urbanism you can organize stocks and flows especially flows for helping the society running like energy, but also food and other items. (C1)"

Another way that looking at flows can identify opportunities to reintroduce materials back into the loop consequently conserving virgin natural resources, is by looking at what is already there and not only designing for the future.

"…it is also stocks and flows of materials, which are mobilized, which are not well used. (C1)"

All those insights on flows come as a complement to defining the basics of circularity in the built environment but to a more practical engineering side, and they completely link back to project CO2RDERES that had at its core the circular value of valorizing the regional flow of secondary raw materials by reinjecting them into the loop as opposed to the alternative of considering them as a *beginning-of-life-cycle* waste (since they are generated during the first step of raw material production for the construction industry).

6.1.1.1.4 Divergences on the concept of circularity in the built environment

Part of what makes this research valuable is the different views that practitioners have on the topic, thus creating a need to study those differences. While the different experts that were interviewed unanimously regard circularity as a positive strategy, the two main differences are the timeline and the scope. Some limit their views to the technical environmental aspects (see the positivist – material technology sphere Figure 76), others go beyond to include social aspects in their definitions and even venture into for example perceptions that question the need of new buildings in first place. Regarding the timeline and the urgency for action, it also is connected to the views. The more complex a view of circularity the participant presented (i.e. holistic and transformational as opposed to techno-centric) the more urgency they expressed for implementation, and vice versa.

"I would say things are changing, but yes, the way people are appreciating the urgencies is limited. We focus mainly on climate change, but [there are] plenty of planetary limits, boundary limits, which are totally exceeded for a long time and the urgency is already there, but the perception of this urgency is really limited. (A2)"

The circular economy has been criticized for neglecting social dimensions as discussed in the literature (section 2.2.4), and although some aspects like enhancing ecosystem functionality and human well-being are acknowledged ever more in the discourse, the focus on material aspects limits broader systemic considerations [332]. This is also reflected in the interview data "*So, the goal should be to set up businesses that indeed function according to the principles of circular economy and are able to deliver these needs to our society and have nevertheless, also respect to the natural boundaries. (C1)"*

Ways of change for circularity is also present in the discourse and came consistently as an extension of the scope of a given definition during the interview, although these insights develop further during the conversation, some of them surfaced as early as in the first block of questions.

"One of the pitfalls of the circularity discourse is that it comes with a certain techno-optimism in a sense that if only we reorganize the production system and use digital technologies and so on, we can continue as we did in the past, to the detriment of a, I think quite fundamental question whether for each, and every building, one should consider whether this building is needed. (C2)"

To better understand the views of interview participants and connect their conceptual understanding of circularity in the built environment through circular design concepts with the R-based circular actions principles, two tree map graphs were generated from the data by counting the positive references in each interview text to each of the actions or design concepts present, to illustrate and link the conceptual understanding of circularity and the divergences. The tree map graph was adopted here to show a distribution over an area. It is divided into rectangular segments, each representing a portion of the whole which adda up to 100 percent. The size of each segment is proportional to the quantity it represents, and the related design concept or action are identified in the labels on the graph.

Figure 77 shows the distribution of R-actions in the discourse in all interviews. Note that *recover* in the actions mentioned does not relate to energy recovery as it is used in some literature especially in waste hierarchy levels, but rather refers to the regenerative action of recovering nature and other spaces. In Figure 78, the circular design concepts in the built environment described in the literature are counted and their distribution presented in the graph.

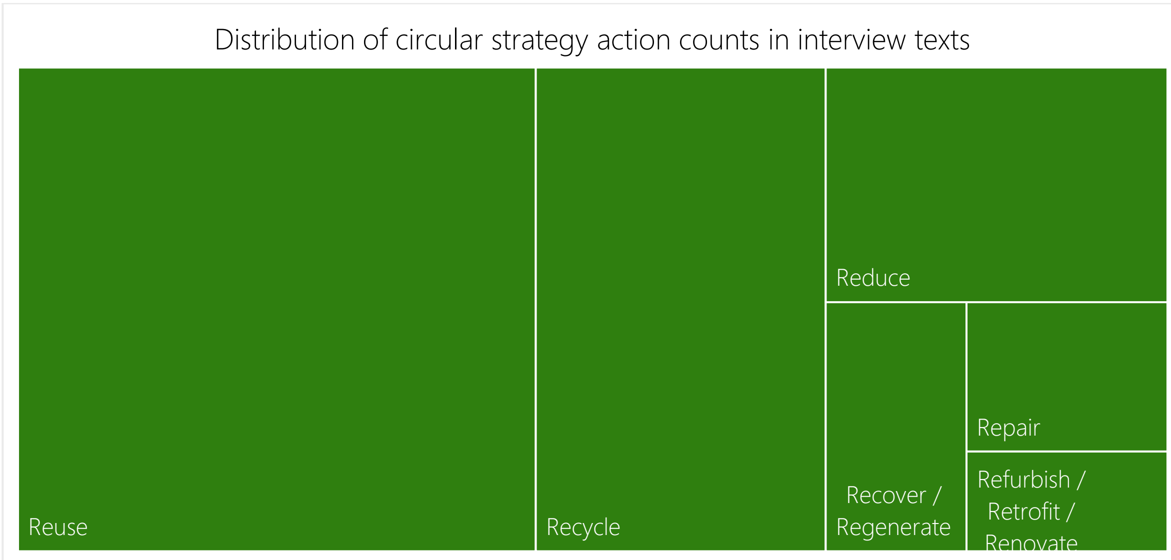


Figure 77. Treemap distribution of circular action counts in interview data.

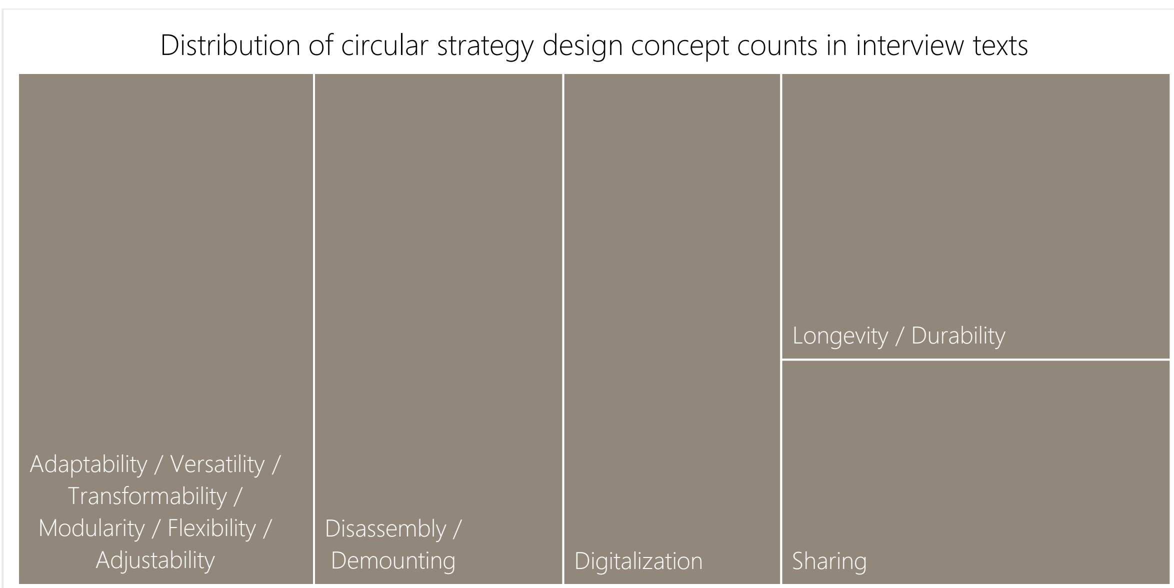


Figure 78. Treemap distribution of circular design concept counts in interview data.

Although the focus of this research is not the discourse analysis of the interview content, it is interesting to study the relation between the R-strategies as action elements for circularity and their link to the circular design concepts. When circular actions are defined by the R-strategies, there is a scale ranging from least to most circular i.e. recycle to regenerate respectively.

Given the quasi-equitable distribution of the design concept counts in Figure 78, which in other words means that they are equally and proportionally present in the discourse, one would suggest that the most circular R-strategies would top the count in the actions, and this is not what happens. Recycling and reuse take more than 50% of the mentions in the text. Therefore, the connection between the circular design concepts and the circular practices could not be fully established as there is an imbalance between the discourse on design and action. Although stakeholders know and recognize the pathway towards transition as well as the final goals of it as the results show, there are clearly multiple reasons that do not help to move forward, and it is one possibility that what are considered good examples are reflected in concrete actions rather than in theoretical design concepts, therefore if these actions are closer to a linear concept (action) but framed as circular (design), they are most likely not in line with circularity principles as such and will continue to perpetuate the linear economy models under the guise of circularity.

6.1.1.1.5 The golden standard for circularity

Complementary to discussing the different definitions of circularity and the views that each of the participants showed is the golden standard that each of them holds as the highest benchmark of practice and outcomes in circular economy. The input given from the interviewees reflects and confirms their previously mapped views on the extents of their holistic approach to circularity.

A shared golden standard goes through three axes:

(1) Stakeholder collaboration

A collaborative view of circularity requires *"A circularity where different stakeholders rethink how they work together with the constraints to ensure economic survival (A1)"*. Although it is narrowed down to the economic aspect here, collaboration is essential for circular oriented innovation that involves the stakeholders sharing the same values [333].

(2) Circular design and construction principles

In advancing circularity within the built environment, it is essential to focus on design strategies that prioritize it such as "*Design for reuse and adaptability, carbon emission reductions, and reduction of CDW and soil excavation, but the goal is not to achieve circularity (B1)*". This involves creating "*an infrastructure that can support different uses, adaptability, durability, healthy materials (B3)*" and planning *"with function in mind, multi-purpose use, adaptability, and down to the very detail of how we assemble different products in the construction (C3)"* to facilitate the future.

Furthermore, embracing the principle of "*no new buildings and new constructions (B2)*" underscores the importance of utilizing existing structures to their full potential and avoiding extra impacts associated with new constructions as a circular strategy.

(3) Overall connection to sustainability

"To achieve the objectives of society without stretching the natural capacities of our world (C1)" is a vision that requires a holistic well-thought approach to circularity in the built environment despite the absence of net-positive regenerative nuance. This involves balancing environmental and social aspects *"to keep the built environment living as long as possible but also not doing it at the cost of comfort and the quality of life of people (D1)"*. The way forward with circularity in the built environment then revolves around finding a "*kind of a harmonious balance between optimums (A2)*"

A golden standard set around following circular design strategies should be critical to ask in first place important question such as "*what's needed, what size of buildings is needed, what kind of materials are needed before even thinking about the circularity aspect (C2)*", in a way that sufficiency is brought into the picture just like in asking oneself whether new buildings are needed or not, and whether brownfield development is not already an answer to many of the questions regarding space and human urban expansion.

Moreover, a critical factor of a good circular strategy is fostering a cultural shift with awareness that has the power to shift things and where new solutions are viewed as natural progressions without the customary skepticism, as stated by one participant "[*We need a*] *habits change that, for example you would use secondary material like other materials, and that circularity comes naturally to everyone [through awareness] (A3)*". Through a change of habits, the construction sector can move away from the current waste reduction concept and into only using renewable resources, *"we should really try keep the highest value possible, so to not produce waste, but to only produce something which keeps the value (D2)"*.

The pattern that emerges from this section is that the collective outlook on circularity follows the conceptual definitions with the idea that circularity is a means towards transition but adds on top of the technocentric approach an element that shifts the discourse closer to the reformist holistic regenerative circularity (see literature section 2.2.7, Figure 29) view when interviewees state awareness, not producing waste, objectives of society, human comfort, etc. It is important to note that this view of circularity is not unanimous among interviewees but appears to be the dominant discourse especially when talking about the ideal standards that they would consider as best practice and best scenario.

6.1.1.1.6 Connection to CO2REDRES

Based on the presented results, the ontological understanding of circularity - encompassing its scope, definitions, and the extent to which it is viewed as technocentric or transformative - significantly influences the research, adoption, and implementation of SCM practices in concrete technology. Variations in how circular practices are understood and prioritized reshape the goals, processes, and strategies within the industrial ecosystem, driven by the perceptions of decision-makers and stakeholders.

Affirmative views of circularity, which emphasize solution-oriented thinking, holistic approaches, and measurable positive impacts, can facilitate a meaningful shift toward sustainability. However, critical perspectives such as viewing circularity as an evolving concept requiring ongoing refinement to achieve an effective transition are equally valuable. These perspectives ground the discussion in practical realities, bridging theoretical ideals with actionable solutions through innovation, collaboration, and systemic change.

Therefore, this analysis raises further questions about the gap between concept and action, as it has been observed in the interview data (Figure 77 and Figure 78), and to which extent is it related to the understanding of circularity in a holistic way. The described gap could represent one of the reasons as to why certain circular concepts are known, studied, and verified – as is the case for SCMs – but are not placed in action on industrial scale from the conceptual point of view of circularity.

6.1.1.1.7 Challenges and barriers to circularity in Luxembourg

In the specific case of Luxembourg, there were many challenges that were mapped throughout the interview analyses. Those were then grouped into 8 categories and are described in this section.

6.1.1.1.7.1 Design and construction practices

- *The difficulty of potential reuse of buildings and building elements.*
- *Optimizing buildings for a single function as opposed to flexible or adaptive use.*
- *Handling buildings as depreciating assets.*
- *Skills and labor shortages in construction and deconstruction.*
- *Conservative culture and traditional practices in construction.*
- *Design preferences aligned to linear practice and reluctance to use reclaimed materials.*

The difficulty of potential reuse of new and old buildings (adaptability) and building elements (disassembly) alike presents a significant challenge in the construction industry in Luxembourg since circular concepts have not yet reached the core design of buildings and often, buildings are optimized for a single function rather than designed for flexible or adaptive use, limiting their potential for reuse and adaptation to new purposes." … *how to make sure to transform this and then we realize, no, that's not possible because we have applied a [limited design] strategy all of a sudden, we are unable to transform the building to the next use. (B3)"* This approach is reinforced by the conservative culture and traditional practices in construction further delaying progress, as there is a strong preference for conventional methods and materials. *"The conceptual and practical work shows that we as humans are not willing to change our routines in general, so the easiest is just to continue like we always did, and this is a big problem. (B2)"* and "*It is a sector that has a certain way of doing things and it's difficult to push them towards changing these practices. (B1)"*

Another concept connected to design, but this time of the financial structures of businesses and how built assets are seen in the current economic system is the handling buildings as depreciating assets, which discourages investment in their long-term adaptability and circular design for longevity. "*The way we handle buildings, we handle them as waste because we depreciate it down to 0, so if we want to make circular economy happen, we must change that. That's the only thing that must change and we must stop incentivizing writing down buildings down to 0, because that's what we do today. (B3)"*

Furthermore, the industry is troubled by persistent skills and labor shortages in both construction and deconstruction domains coupled with the idea that we need to build more and faster to satisfy the growing demand, exacerbating the difficulties in implementing circular strategies. "*The construction companies need to have the skills and the right people, which is a big problem for them, because for the moment they are lacking labor, and they are lacking even more, skilled labor … and the same is true for the deconstruction companies. They are big operators of machines, but they have no skilled labor to do proper disassembly. So, these are the big stoppers [for circularity]. (C3)*"

The progress in adapting circular strategies for a better built environment is further impeded by the rigid practices in the construction sector, as there is a strong preference for the use of conventional methods and materials as opposed to other industries. *"The industry is trying to catch up, so the ones that are really product-oriented change faster because they have worked for example on lean processes … whereas construction is still kind of behind, it's partly linked to the industry, but still also something that is handmade, kind of traditional in a way. So, it has a great inertia in terms of changing habits. (D2).*" A mindset shift oriented towards innovation seems to be what most interviewed experts across the three sectors see as a challenging aspect towards change. *"Construction is typically a lagging domain in terms of innovation. (A2)" and "I think big changes everywhere [are needed], starting with our mindsets, our society, how we function, etc. (D1)"*

Moreover, design preferences that align with linear practices *"designers that, that are not keen on thinking with reclaimed elements. (A2)"*, and a reluctance to use reclaimed materials due to perceived risks or aesthetic concerns only add to the challenge both from the designer and the client perspective. *"Innovating with reclaimed elements is also a bit taking some risk. Yeah, the risks now are a bit, too high to make people being ready to dare and to try. (A2)"*

From the practice side, a lot of the actions of today are based on past experiences that do not relate to a circular future and how things will be done "*So the big challenge today in designing is really thinking hard about potential reuse of buildings, moving forward, instead of optimizing it for a single function, which I think is a very, very dangerous path we are taking, I'll give you another example, we build schools starting with the principle that we will educate in schools for the next 50 years like we have always done. Somebody standing in front having a wall to project something on and there are kids sitting in front of you and you teach them something. (C3)*"

6.1.1.1.7.2 Regulatory and policy related challenges

- *Overregulation (at certain level/disciplines not related to circularity) and inflexible norms.*
- *Legal barriers and certification issues.*
- *Taxation policies on reclaimed elements.*
- *Lack of government regulation to promote circular economy.*

Overregulation and inflexible norms pose significant obstacles to the adoption of circular practices in construction, making it difficult for the industry to innovate and integrate sustainable methods effectively. These stringent regulations often limit the ability of builders to experiment with new materials and techniques that are essential for circular construction.

> *"I see some more and more, we are over regulated, too much too many norms we come up with, which makes it just almost impossible to think smartly about the building. It's all about following rules but following rules does not allow smart decisions. (C3)"*

Legal barriers and certification issues further complicate efforts to implement circular economy principles. The process of obtaining necessary certifications for reclaimed materials can be cumbersome and costly, creating additional hurdles for their use. Legal barriers. *"There are also legal barriers. It's still difficult, for insurability questions to get a certification or to get a kind of validation in the design of certain materials, you could have some breaks from your insurer… (A2)"*.

Taxation policies on reclaimed elements also act as a limiting factor, imposing financial burdens that make it less attractive for builders or their clients to choose sustainable alternatives over new materials. "*There's also the taxation that is not helping because why having a second taxation on reclaimed elements? (A2)*". Such subtle details in tax policies, sometimes unnoticed by the administration, contribute to a policy that fails to recognize the environmental benefits of reusing materials, instead perpetuating their status as less desirable options and furthering the challenge.

Moreover, the lack of government regulations and policies to promote a circular economy exacerbates these challenges in the view of some experts *"I fear that without any regulation / policy from the government it might be hard because certain stake holders are earning a lot of money. (B2)"*. Without clear policies and incentives from regulatory bodies, there is little motivation for the industry to shift towards circular practices when they would cost more, and the market is embedded in the current profit-maximizing economic system. *"In circular economy, the key driver is you've got a better solution for the same price or the same performance for a lower price. That's a winning* *strategy. Now, if you don't find that spot you are not meeting the market needs ... that's how the economy works today. So, these technologies wait for regulation to hit so the customers don't have a choice, but that's a long way. (C3)"* However, it is certainly connected to the cost of circularity. If it were cheaper than the linear construction strategies, it would likely not need regulation to change, and here the importance of systemic change as a solution to such challenges becomes clearer.

This absence of supportive regulation means there is insufficient promotion of sustainable building methods, leaving the industry reliant on the good will of its stakeholders and decision makers who are often not willing to do anything about it mostly because of economic considerations.

6.1.1.1.7.3 Economic Considerations and the Cost of Circularity

- *Short-term profit vs. long-term sustainability*
- *Cost implications of circular economy practices*
- *Financial incentives and business models*
- *Economic inertia and vested interests in the construction industry*

As shown in the previous point, with the interaction of policy and market practices, it is clear from the interview data that economic considerations present substantial challenges for implementing circular strategies in the built environment, creating significant barriers to the adoption of more sustainable practices. One of the most prominent issues is the conflict between short-term profit and long-term sustainability. Many stakeholders in the construction industry prioritize immediate financial gains, often driven by market pressures and shareholder expectations, over investments that would yield long-term environmental and economic benefits. This short-term focus discourages the adoption of circular practices, which frequently require higher initial costs but promise greater savings and environmental advantages over time. "*A big challenge is financially integrating and having a short-term profit over long-term, how to integrate the long-term view in the short-term world where everything is looked at in short-term (C3)*".

Connecting time and money, two important variables of today's economic models, makes things harder for circular solutions that require investment and development, *"I would say most of the things [you can do], but if you do that it takes work. It takes more money, it takes more time, lots of more time (D1)"*. This affects not only the business models *"...it's difficult for them to completely change their business model overnight. (B1)."* But also the consumers, where not all are willing or able to pay a premium for circular products, especially if the product in question is a house for example and not a consumer good, "*it must be affordable. (C1)*". "*If you have to pay 10,000 euros more, would you be willing to do that? And if you look at your personal purchasing decisions, somebody says they pay premium of 15%, because it saves* CO_2*. How often are we personally willing to do that? (C3)*". Paradoxically, lower overall prices due to reuse or retaining existing structures for example, in certain projects where remuneration structures are tied to a percentage of the total project value, might constitute a potential disincentive for such circular measures, as these practices can reduce the overall project cost—and, consequently, the stakeholders' compensation. "*If you reduce the cost by reusing or by keeping [existing structures] then you are not paid the same. (A2)*"

In addition to the data from the interviews corroborating this challenge, the cost of circularity has been cited [166], [334], [335] in multiple reports and studies as a classic barrier to the adoption of its strategies, due to high upfront expenses as previously mentioned where these initial investments can be a significant deterrent for developers and contractors who face financial constraints "*also parts of the construction actors that could be involved in these are the ones that have the less margin to innovate also to change the system because most of the [profit] margins are not done by those actors (A2)*". This results in a conflict of interest among stakeholders because on top of the cost barrier, "*The people who make the most money from the sector are not the same people that would benefit from inserting circular concepts and think of sustainability. These are not the actors that could change the game (A2).*"

In addition to the prior challenges, economic inertia and vested interests within the construction industry further impede the transition to circular strategies "*there's a big inertia in the system, and a lot of stakeholders, which earn a lot of money by making no change, so the vested (interests) rights are enormous in the construction industry (C3)*". Established companies and stakeholders often have significant investments in existing processes, technologies, and supply chains that are aligned with linear economic models. This creates resistance to change, as moving towards circular practices would require substantial shifts in operations and potentially diminish the value of current assets "*I think in the moment, really the stakeholders that are there are maybe not so motivated because they have a business model that is working (A3)*".

The Idea that the related industrial actors might have different takes depending on where they are present in the value chain was very clear in the data. If they are on the further edge and they do not benefit from circular practices (e.g. would sell less, or there is no added value to pass on to the price, etc.) they might support it less than someone who would benefit from it financially. This is one of the costs of implementing circular strategies in an economic system that is centered on profit only. In the current economic system, it always has to be profitable to everyone along the chain, otherwise it risks being sidelined. This relates a lot into stakeholders and how they act and interact in ways that promote circularity or stall it. *"I see maybe construction companies are more open towards [using circular products] because they are maybe further down the value chain [than manufacturers] (B1)"*.

From the interviewee's perspectives there seems to be a consensus that in today's system with the insufficiently developed circular business models, together with the absence of robust incentives, on top of the cost of circularity, there is not enough motivation for companies to invest in circular practices from an economic point of view. Many business models are built around an old status quo and do not account for the long-term value of sustainable practices in the sector, which even linearizes otherwise circular practices to adapt to its models, and not vice-versa.

6.1.1.1.7.4 Logistics and Infrastructure

- *Lack of logistics and digital/physical infrastructure*
- *Challenges in material flow and storage platforms*
- *Time-consuming processes and higher costs*

As previously discussed in the definitions section, the relationship between circularity and energy and material flows is clearly one of the most important aspects when speaking of closing and narrowing loops in biological and technological cycles. Effective circularity demands adequate logistics and infrastructure, *"there is certainly a barrier in terms of logistics, in terms of the tools, the infrastructure that has to be put in place now to allow for these flows of materials to actually go from one building to another or for a building to be built (B1)"*. This applies to both "*digital infrastructure and physical infrastructure (B1)"*. There is also the need to track, manage, and move materials efficiently *"through digitalization (A1)"*. With the logistical challenges managing the flow and storage of reclaimed materials becomes difficult for example and *"time consuming and it costs more, so we tend to recycle instead. (A1)"*

6.1.1.1.7.5 Innovation and Technology

- *Innovation in construction vs. product-oriented industries*
- *Technological advances in recycling and reuse*
- *Biobased materials and limitations on natural resources (also fits under environmental constraints)*

The penetration of innovative practices in the construction sector often differs substantially from the product-oriented industries as already discussed in the economic considerations previously as well as from the design perspective considering that "the conceptual work, and practical work shows that we as humans are not willing to change our routines in general, so the easiest [in the sector] is just to continue like we always did, and this is a big problem [for the sector]. (B2)". This, allied to the perceived *"conservative aspect or culture in construction. (A2)"* hampers innovation at a wider scale.

However, there is more than the described inertia to innovation that comes up multiple times during the interviews. The technological advances in recycling are not widely applied to the construction engineering sector, and even with the increasing improvement in research and innovation efforts, most of the recovered materials are downcycled and the processes that deal with such material flows are not optimized for the complex and large-scale needs of the built environment.

Transitioning from technical innovation to material technology, the challenges of supply (quantity) and performance (strength and durability) of new hybrid materials or biobased materials are constraints that limit their adoptability. "*...Although [belonging to the] biological cycle, and we are talking a lot about biobased materials, there are also limits to digging into nature to getting out materials, so we have to make sure that both technical and also biological resources or not overstretched. (C1)*". In addition, the use of biobased materials is often limited by factors such as availability and cost on top and relying heavily on them might lead to the overexploitation of natural resources if not managed carefully in a way that is balanced with the need to protect ecosystems, adding to the complexity. The problem of availability was also one of the barriers to the implementation of industrial scaling of solutions studied in project CO2REDRES, since the availability and variability of the researched materials was not considered compatible with the needs. Hence, the supply conundrum is not only limited to biobased materials but also to certain SCMs due to homogeneity issues and availability.

6.1.1.1.7.6 Mindset shift, Stakeholder Engagement and Education

- *Awareness and willingness to change among stakeholders.*
- *Educational needs for architects, engineers, and other stakeholders*
- *Psychological barriers and perceptions of reused materials*
- *Importance of collaboration and integration in environmental initiatives*

Many stakeholders are unaware of all the existing technical possibilities for circular construction due to a lack of continuous education updates and sensitization. *"there's also the sensibilization, the education, a lot of stakeholders are not aware of the different possibilities which already exist technically (A1)".*

There is also the fact that certain designers who resist updating their knowledge tend to offer clients conventional building solutions *"as it has always been done"* with little to no innovation when it comes to circularity. Moreover, the importance of education and formation was cited as a challenge at a grand scale since events and courses are always there but do not seem to get to the big part of practitioners, *"an architect or an engineer … who does not want to develop himself, will always propose to the client the same kind of building, with minor changes [at best]. (A1)"*

Psychological barriers to the adoption of reused materials or elements or even new unconventional materials exist, and these are barriers where reuse is associated with low quality, despite this being a misconception as many reused materials are just as effective as new ones. *"There are definitely psychological barriers in people's minds, reuse means cheap means medium quality. Yes, means something that could be very improved by if it was new materials, which is totally false. I think from many materials [perspective] it doesn't matter because you don't see them at least or very few (A2)".*

Finally, successful implementation of environmental initiatives requires collaboration, as no one can achieve these goals alone; integrating circular practices into mainstream activities requires collective effort and cooperation. *"To bring the things together, it's really what you need that you have people to bring things together, which is also, let's say, from my experience is that everything you do in the environmental sector you can never do alone, you always need people that are willing to transport it, to their main activities, because it's an add on often and you have to integrate it in other things (A3)".*

6.1.1.1.7.7 *Environmental constraints*

- *Reducing environmental impacts (e.g., CO2 emissions, concrete production)*
- *The focus on energy efficiency and not holistic approaches*
- *Goals for reducing construction impact by 2030*

One of the goals of circularity is the reduction of environmental impacts, so naturally there are significant challenges related to that aspect. In the context of concrete, while SCMs can reduce the carbon footprint of concrete, the supply and processing of SCMs (e.g., transportation, activation of certain materials like fly ash or slag) may still contribute to emissions, therefore offering a reduction but not an elimination of emissions. Additionally, reliance on industrial by-products like fly ash ties circularity to industries (e.g., coal-fired power plants) that are themselves environmentally unsustainable promotes a less harm philosophy rather than a regenerative circularity approach. *"We need to know from which processes do materials come from as well... (A2)"*

Another challenge remains in the focus on energy efficiency over holistic approaches. Circularity efforts often prioritize energy efficiency, which, while crucial, may lead to unintended consequences such as narrowing the focus on energy metrics and overlooking systemic interdependencies. A technocentric approach that prioritizes energy efficiency matters such as reducing energy in production processes may overlook broader impacts, such as material sourcing, lifecycle emissions, and end-of-life recycling. A failure to embrace a holistic view can result in siloed solutions, as noted by one interviewee that "*focusing only on solutions that optimize concrete production in terms of energy might ignore [the potential] to use the material to design buildings for disassembly or reuse*."

Ambitious targets for reducing construction impacts such as carbon neutrality or material circularity face multiple obstacles including a time one *"If you look at this timeframe, 2030 is very, very near and we have to reduce for Luxembourg in around 65% the impact of the construction sector (C1)"*.Existing building codes may not adequately accommodate innovative solutions such as SCM-based concretes fast enough, slowing adoption and scaling. Meeting the next decade's targets requires buy-in from stakeholders across the value chain.

6.1.1.1.7.8 *Practical Implementation challenges*

- *Practical difficulties in achieving 100% reuse*
- *Complexity and feasibility of implementing circular economy practices in real contexts*
- *Logistical and practical barriers to circular construction*

While the ideal vision of circularity in the built environment emphasizes complete reuse and zero waste, "*achieving 100% reuse in practice is extremely challenging, especially in the case of old buildings (D1)*". Not all building components can be reused without extensive processing or with the same structural integrity and performance, which may require additional energy and resources, sometimes making it less sustainable than using new materials. Furthermore, design constraints and compatibility issues arise when integrating reused materials into new projects such as is the case in materials like the ones studied in project CO2REDRES, as they may not meet modern standards or fit seamlessly into contemporary architectural and engineering designs. Additionally, the lack of standardized methods for material recovery, testing, and certification makes it difficult to ensure quality and safety, creating reluctance among designers, developers, and regulatory bodies, "*but this is slowly changing, maybe it need to be faster* (B3)".

Existing linear economic models—which prioritize extraction, use, and disposal—are deeply embedded in supply chains, making it difficult to shift to circular alternatives. The feasibility of circular practices is also influenced by economic factors, such as the "*higher upfront costs of deconstruction compared to demolition (A3)*, *the unpredictability of secondary material availability (A1)*, and the *market demand for reclaimed components (B3)*". Furthermore, when short-term financial gains take precedence over long-term sustainability benefits the choice tends to go to the former rather than the latter, so the challenge is on top *"how to make construction cheaper again (C3)*". In real-world projects, circular solutions often remain pilot initiatives rather than mainstream approaches due to these systemic and financial barriers as is the case with many projects cited by the interviewed experts.

Circular construction also relies on effective logistics, but multiple barriers hinder its scalability. Material recovery and storage present significant challenges, as salvaged materials require space, careful handling, and efficient tracking systems to be successfully reintegrated into new construction. This also applies for raw materials even in the case of project CO2REDRES where one of the main points for valorizing waste or secondary products is the benefit of not needing space for storage. Unlike standardized new materials, reused components vary in size, shape, and condition, necessitating flexibility in design and construction methods, which is not always feasible in large-scale developments. Additionally, "the *lack of supply chain coordination* (A3)" between demolition contractors, material suppliers, architects, and builders makes it difficult to establish a smooth circular flow of materials, "*everyone knows how to do it in a linear economy and it's easy like* *the pathways are set up, we don't have to go looking for something new or think out-of-the-box. (D1)"* Moreover, the construction industry operates under tight project timelines, and circular practices for now require additional time for sourcing, "*testing, and adapting reused materials (B3)*", which can discourage their adoption in fast-paced urban developments.

6.1.1.1.7.9 A system of integrated solutions

The final summary of the various challenges mapped in this section synthesizes them into seven interconnected categorized aspects: market, policy, environment, business, technology, social, and cultural. These aspects, shown in the inner circle at the core of Figure 79, are separated by dotted lines, indicating porous boundaries. This design illustrates that solutions can flow between the aspects and that the aspects themselves are not isolated from one another but rather work in harmony and often influenced by one another, in a way that an action or a solution that affects one might directly or indirectly relate or affect another, just like in an interconnected system of feedback. Surrounding these core aspects is the second ring that presents suggested actions for promoting circularity, with each action targeting two of the core categories. The mapping of those solutions and the links to the studied aspects arose from the synthesis of the results that informed the challenges discussion earlier in this section.

The representation of concentric circle implies that they can both turn around a locus i.e. the fixed center that connects the circles and therefore bring forward the idea that any solution is not unique to one challenge but there can exist elements that overlap. This provides a systemic view that is often missing when stakeholders see solutions as punctual and restricted to one aspect that they are studying.

The outermost dotted circle represents the holistic integration of the solutions through a combined view of the challenges that circularity faces through a system that allows those transitions to happen and fosters stakeholder engagement and economic viability to advance further.

In practical terms, the figure can be regarded as an ecosystem of solutions designed to foster systemic change and assist in the transition towards a regenerative circular economy because it takes into consideration how different strategies can work together to address more than one aspect at a time all while really focusing on creating important shifts in how nature, resources, and society connect to a regenerative circular economy design that can reshape how stakeholders understand and deal with circularity issues and challenges on a broader level. On a more specific level, such as a certain product or material, the questions can be redirected from the figure by asking if the awareness and engagement have been created, if the value added of that solution is net-positive not only in terms of financial profit, etc. It is evident that other solution pathways exist beyond what the interview data suggested and those can also be used in this template by substituting in the sections and assessing how it affects the related aspects.

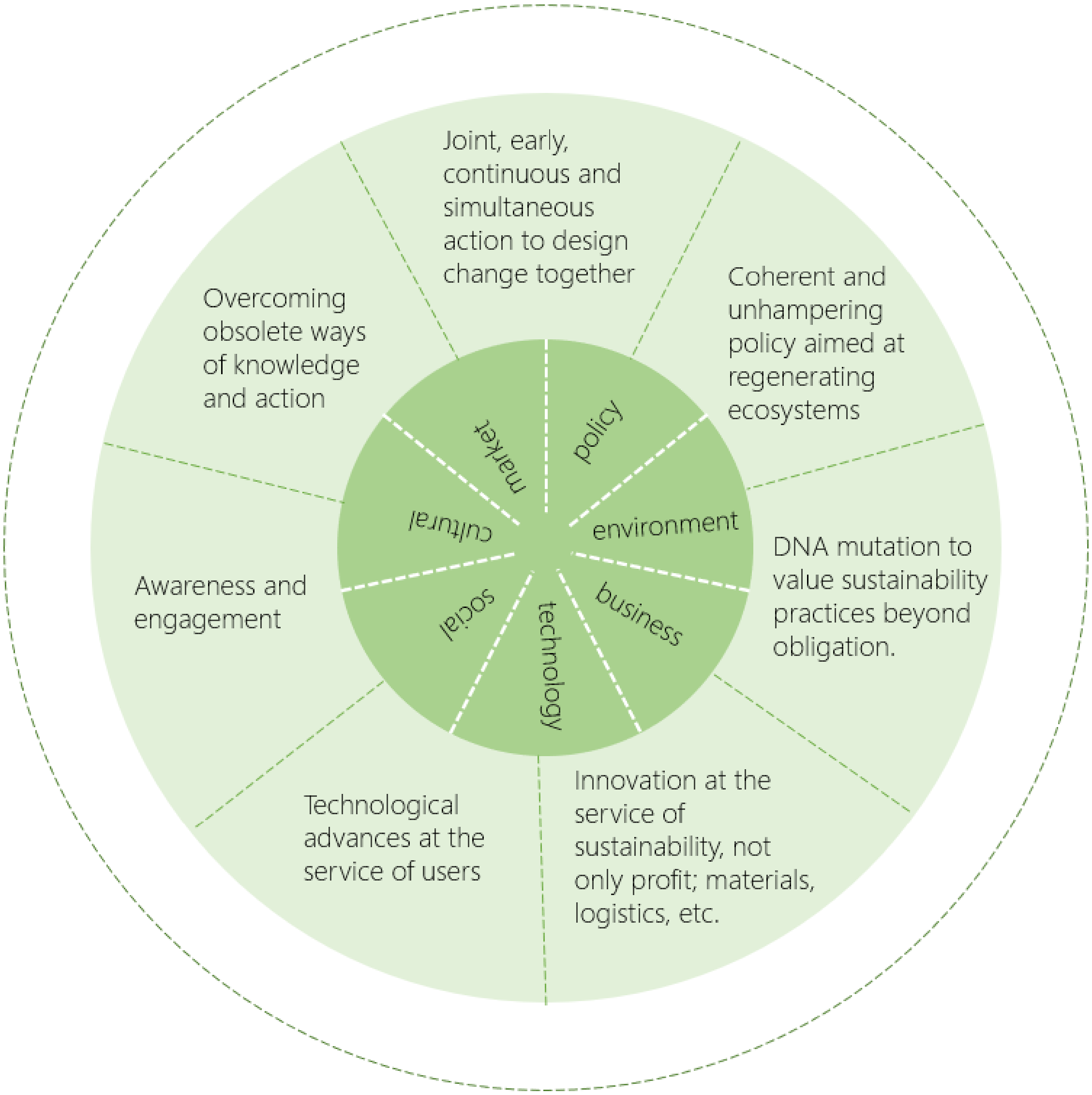


Figure 79. The system of integrated solutions for change for circularity conceived from the challenge mapping (context clarification: DNA mutation is a figure of speech for a structural shift or change).

6.1.1.2 Stakeholder interaction and relational mapping

This section answers research questions h and k

The stakeholder interactions that were studied in the interview data are represented in the map of

Figure 80 which illustrates the interconnected network of actors involved in circularity in the built environment in Luxembourg. It highlights key stakeholders across various sectors, including businesses, policymakers, non-governmental organizations, and communities, while emphasizing the dynamic and overlapping relationships among them. The stakeholders were mapped by using the coding system presented in the methodology during the interview data analysis from the answers given to questions related to this part in the annexes in section 10.1. The interviewees were asked to identify the stakeholders that are influential and influenced in the context of CE in the built environment and rank their importance. As the ranking did not prove relevant, the analysis was then done on a horizontal basis considering all cited stakeholder groups as important players.

These connections are crucial as they represent the pathways for collaboration, knowledge exchange, and resource sharing with the objective of advancing circular design and practices when exploited in a constructive manner. By fostering strong, synergistic interactions, complex challenges can be addressed, and diverse interests aligned through ensuring coordinated efforts toward common objectives.

This map serves as both a strategic tool and a visual representation of the ecosystem, underlining the pivotal role of relationships in driving impactful, sustainable outcomes (more on that in the matrix that details each connection). Most importantly, while thinking of stakeholders, and analyzing their connections through actions, an important aspect that emerges is the difference in agency, influencing the understanding of the agents that should influence system changes.

Figure 80. Stakeholder map of circularity in the built environment in Luxembourg

Legend: The figure shows a scale on the outermost circumference which is the number of connections of each node towards the partner stakeholder on the other end of the node. The color of the connection coincides with its origin but is of minor importance in this exercise because the interviewees were not asked to identify origins and destinations but rather connections. The thickness of each connection is proportional to the number of connections mapped between two stakeholder groups with a minimum of 1 connection per group represented in this figure.

	architects	building owner	building owner – inhabitants	building owner – institutional	business developers	construction companies	consulting services	craftsmen	deconstruction companies	educational institutes	engineers (design, planning, execution, etc.)
architects		-	-	-	-	-	-	-	-	-	-
building owner	Architects can advance the transition of the BE by offering more circular solutions to clients. *A1 pos 53*		-	-	-	-	-	-	-	-	-
building owner – inhabitants	-	-		-	-	-	-	-	-	-	-
building owner – institutional	-	-	-		-	-	-	-	-	-	-
business developers	-	The building owner as the client has the final decision of what to build and how much money to spend thus impacting especially the business development plan. *A1 pos 48*	-	-		-	-	-	-	-	-
construction companies	-	-	-	-	-		-	-	-	-	-
consulting services	-	-	-	-	-	A mutual relationship – which degree of innovation to adopt faced with challenges of circularity, assessment of what can be done, and what is considered too risky.		-	-	-	-
craftsmen	-	-	-	-	-	-	-		-	-	-
deconstruction companies	-	-	-	-	-	Crucial connection from the technical aspects point of view – for material compatibility and practical exchange. *A3 pos 34*	-	-		-	-
educational institutes	-	-	-	-	-	-	-	Training opportunities and skill update to craftsmen as means to overcome barriers related to know how of innovative constructive systems use. A2 pos 37	-		-

	architects	building owner	building owner – inhabitants	building owner – institutional	business developers	construction companies	consulting services	craftsmen	deconstruction companies	educational institutes	engineers (design, planning, execution, etc.)
engineers (design, planning, execution, etc.)	The conversation is crucial for systems-design-thinking that would promote transition throughout the whole life cycle and not only conception. *C3 pos 20*	-	-	-	-	-	-	-	-	-	
244uropean commission	-	-	-	-	-	-	-	-	-	-	-
financial institutes	-	Interested in safe investments and creating financial return *C3 pos56*	-	-	-	-	-	-	Financial investors seek some return on value of materials once monetized. *C3 pos56*	-	-
insurance companies	-	-	-	-	-	A closer collaboration for policies that are encouraging to push new materials and techniques without overquantifying risk and holding back circular solutions. D1 pos 115.	-	-	-	-	-
IT providers	-	-	-	-	-	-	-	-	-	-	-
lawyers	-	-	-	-	-	-	-	-	-	-	-
logistics companies	-	-	-	-	-	-	-	-	Solutions for integration of flows of reused materials and elements into the business and considering a wider connection between suppliers and buyers. C2	-	-
maintenance companies	-	-	Promoting circular practices such as repairing rather than replacing, shared services, etc. A2	-	-	-	-	-	-	-	-
material suppliers and manufacturers	-	-	-	-	Suppliers are very powerful and can only engage in meaningful transition by changing their	Establish a dialogue on types of materials that are needed and how to provide adequate sourcing. *A3 pos 44*	-	-	-	-	-

	architects	building owner	building owner – inhabitants	building owner – institutional	business developers	construction companies	consulting services	craftsmen	deconstruction companies	educational institutes	engineers (design, planning, execution, etc.)
					business models. *C3 pos 61*						
public administration	-	-	-	The institutional building owners (e.g municipalities and ABP) have the power to request more circular buildings, push the market and promote innovation. *C3 pos 57*	New laws and dispositions are what pushes for new business models that are more aligned with circular values. *B1 pos. 36*	1. Companies rely on the administration for guidance through beneficial legal frameworks, authorizations, and incentives. A1 pos 55 2. Feedback is expected from construction companies to the administration on what works well or not. *A1 pos 59*	The administration promotes frameworks for sustainable design that makes the shift easier for designers. *A1 pos 57*	-	1. The waste act defines scopes and definitions, but the time-gap element between deconstruction and possible reuse is crucial for secondary materials storage in a country short on physical space availability. *A3 pos 44* 2. The waste law strictness on what can or not be considered waste affects how the deconstruction happens. *D1 pos*	-	-
research funding institutes	-	-	-	-	-	-	-	-	-	-	-
research and innovation institutes	Train design teams to understand circular economy and how to embed it in the built environment *C3 pos 58*	-	-	-	-	A connection between construction companies and universities to suppress the lack of capacity building and human resources. C2 pos 26	New methodologies and ways of thinking taught at universities impact directly the work force and how consultants influence the process. *D1 pos 65*	-	-	Pilots on building materials and circular building techniques that involve all other core and important stakeholders to demonstrate capabilities. C1 pos 75	Train engineers to implement circular economy strategies in the built environment *C3 pos 58*
NGOs	-	-	-	-	-	-	-	-	-	Team up to create and work on future visions that inspire transformative ideas in society. C2 pos 39	-
Certifying bodies (building certifiers, etc.)	-	-	-	-	-	-	-	-	-	-	-
digital platforms	-	-	-	-	-	Digital platforms can collect and store data to maintain the residual value of a building. *C3 pos 64*	-	-	Digital platforms help organize deconstruction much better and connect other stakeholders efficiently. *A2*	-	-

	European commission	financial institutes	insurance companies	IT providers	lawyers	logistics companies	maintenance companies	material suppliers and manufacturers	public administration	research funding institutes
financial institutes	Affected by the influence of taxonomy changes with regards of which of their clients are eligible for loans for example. B1, pos 24.	-	-	-	-	-	-	-	-	-
insurance companies	-	-	-	-	-	-	-	-	-	-
IT providers	-	-	-	-	-	-	-	-	-	-
lawyers	-	-	-	-		-	-	-	-	-
logistics companies	-	-	-	-	-		-	-	-	-
maintenance companies	-	-	-	-	-	-		-	-	-
material suppliers and manufacturers	The power to change things at supplier level is a top-down effort that would happen when they cannot claim that recycling is enough to be circular and have to look at other circular principles to comply with EU regulation. C3	-	-	-	-	-	-		-	-
public administration	Clear and coherent policy alignment to reach green deal targets, and the obligation to follow locally the EU agreements and laws A1 pos 72.	-	Establish a dialogue on risks and coverages with building safety regulations that support a circular future. B1 pos 68	-	Lawyers (and justice system) who start to fight for sustainability through activism or in general defending their representatives' interests have an impact on how the public administration sees the issue. D1 pos. 59	-	-	-		-
research funding institutes	-	-	-	-	-	-	-	-	-	
research and innovation institutes	-	-	-	-	-	-	-	Support from academia through innovative projects and findings to implement in the industry, through collaborations and funding. B1 pos. 21	-	Promoting funding for innovative applied research in circularity in the built environment with connection to the industry. A1
NGOs	-	-	-	-	-	-	-	-	Responsible for pushing the	-

	European commission	financial institutes	insurance companies	IT providers	lawyers	logistics companies	maintenance companies	material suppliers and manufacturers	public administration	research funding institutes
									government and calling for accountability and social engagement for the cause of sustainability. C2 pos 39.	
Certifying bodies (building certifiers, etc.)	-	Building certifiers help create the data for financial investors, and by wanting to stay ahead of legislation can promote innovation and influence the long-term actions. C3 pos 63	-	-	-	-	-	-	-	-
digital platform providers	-	-	-	IT providers are the backbone of digital platforms and could work on ways of continuously improving the platforms for better outcome though understanding the sector's objectives. A2 pos. 83	-	-	-	-	An ally to regulators in proving circular actions and promoting circular design through material offer and traceability. A2	-

By examining these relationships, we can easily identify potential ripple effects across stakeholder interactions. Changes or decisions made by one stakeholder, especially those in key positions like building owners, construction companies, public administration, and financial institutions, can have significant impacts on others, driving the transition towards more sustainable practices in the built environment.

For example, institutional building owners can leverage their influence to demand circular strategies and innovative solutions that align with their vision of a sustainable built environment, thereby setting industry benchmarks and pushing the market towards greener practices, starting with service and product procurement (impacting material suppliers, architects, construction companies) then setting precedents for good practices to be studied and followed allowing innovation to infuse the process with outside input (research and educational institutes), and give back to society by raising awareness to the importance of such actions, and ending up by closing the circle to influence policy for better change.

The matrix and the relational map presented in this section delve into understanding the stakeholder roles and relationships through their interconnections which identifies communication flows between them and underlines the power dynamics, both of which are important insights on the circularity landscape in Luxembourg.

Studying stakeholder connections in this context shows their organization and identifies key stakeholders for each connection in a situational manner. During each interview, the participants were asked to categorize the stakeholders they had identified into one of three categories: core, important and interesting/ed. This led to concluding that the understanding of the network of relationships and the influence of each stakeholder is situational, because apart from a few actors that were always considered core, others varied along the importance attributed to them in the classification due to how their roles are perceived in each person's field.

Additionally, mapping these connections helped assess the degree of influence each stakeholder holds in a qualitative manner and how their interests align or conflict with circularity. This deeper understanding of stakeholder dynamics can enable or unlock the potential for actors to strategize effectively, managing or mitigating potential concerns while fostering collaboration where interests overlap. Recognizing the varying levels of influence also allows for more precise intervention when conflicts or challenges arise.

Furthermore, with a clear view of these relationships and influence levels, the different organizations can design targeted communication or connection strategies that engage stakeholders more effectively. Tailored interactions, based on the needs and influence of each stakeholder, can increase the chances of successfully aligning stakeholders with a project's goals – in this case a regenerative sustainable built environment. Therefore, the intended use of the stakeholder matrix is beyond identifying connections to support strategic decision-making. It is the creation of meaningful engagement opportunities through new interactions that can develop a push towards systemic change. *"There are small and medium sized enterprises who in their very market segment are eager to change things but are facing a couple of barriers and can't become circular on their own because it's so complex and interconnected along the value chain of the building sector, so they have strong stakes, they are interested and they see their future in the circular business model, but yeah, probably lacking allies for doing so, so they need more proper connections. (C2)"*

6.1.1.2.1 Symbiotic connections mapped

Symbiotic connections in the context of a sustainable built environment involve stakeholders whose goals and actions mutually benefit each other, enhancing their collective ability to achieve sustainability objectives. The symbiotic relationships between stakeholders in this section are based on the matrix from the interview data and context oriented to Luxembourg. Some are not directly identified by the interviewees but are the fruit of the data analysis of multiple connections across the presented matrix.

Architects and Building Owners

Architects can provide innovative affordable sustainable design solutions that influence their clients' choices, creating energy-efficient and environmentally friendly buildings by embedding circular design principles that can at least be the same price or cheaper than linear alternatives for a start. This might even help further the market and with further demand lower the prices of circular solutions.

Construction Companies and Material Suppliers

Construction companies that rely on material suppliers to provide sustainable materials that meet environmental standards and project specifications, can increase the demand for sustainable materials and reused elements (also from deconstruction companies) the more they use it, while completing projects that meet sustainability criteria and shift the image of the built environment.

Consulting Services, Material Suppliers and Manufacturers, and Research and Innovation Institutes (including educational institutes)

A multiple-sided collaboration to stay updated on the latest research and trends in sustainable practices, while educational institutes can benefit from real-world insights and case studies, and the industry keeping a step into innovation, even maybe funding it for the development of solutions. This is already done, however the scale and the benefits reaped can still be more substantial by crossing the research edge into industry scale testing and experimentation. The mutual benefit lies in the industrial actors enhancing their expertise and service offerings, while educational institutes ensure their curricula are relevant and practical. The same applies to engineers and educational and research institutes.

Another important aspect is the training and skill building for stakeholders across the sector from architects to engineers and building workers that can be facilitated by educational institutes and professional associations to teach basic and advanced aspects of circularity. "*So, how to train people dealing with buildings at all levels, be it planners, architects, craftsmen, or others. How to train them in a way that they can contribute. (C2)*"

Public Administration and NGOs

A symbiosis that can also be a conflict, but in both ways beneficial to circularity, since NGOs can advocate for, and support public administration initiatives aimed at promoting sustainability while keeping the connection with society. In the case of conflict, NGOs are also known to be vocal about the values and issues they defend, so it is an extra pressure that keeps in check certain acts of the administration.

Research Institutes and Construction Companies / Materials Manufacturers

Research institutes can develop new sustainable, (bio-based or not) materials and circular construction methods through design and experimental research, that construction companies can implement in their projects giving a competitive edge with innovative solutions, while research institutes see their work applied in real-world settings, enhancing their impact, securing funding, and disseminating research and real-life applications of science. This can also influence policy and standardization.

Certifying Bodies and Financial Institutes

Certifying bodies can provide the credentials needed for buildings to be recognized as sustainable, and push for better design, which financial institutes can use to justify investments in green projects and channel funds into better practices. This can be an opportunity driver for circularity, although it could come with an increase in the influence of the financial sector, which is not always regarded as beneficial.

IT Providers and Digital Platforms

The digital platforms are likely to hold an important role in the transition towards a circular built environment especially after the recent EU policies on digitalization for sustainability and the introduction of digital product passports through EU regulation (see section 2.2.7.1). The collaboration between IT providers and digital platforms can be fostered by the understanding of industry-specific sustainability goals that then prompt tailored solutions that directly address the needs and challenges of the sector such as optimizing material usage and storage and waste reduction processes for example.

Moreover, as the implementation and use of various digital platforms becomes widespread in the future, large amounts of data related to projects, resources and impacts can be harnessed by IT providers to derive actionable insights and even real time monitoring to deal with sustainability challenges predictively rather than posteriorly.

IT providers contribute their technological expertise, while platform developers and industry professionals offer insights into practical, on-the-ground needs. This mutual exchange ensures that platforms are not only technically robust but also aligned with the real-world requirements of sustainable and circular construction.

Material Suppliers and Deconstruction Companies

The relationship between these two actors is one of a direct correlation to the degree of advancement of circularity. By fostering a two-way collaboration both play a pivotal role in promoting circular actions and pushing away from the concept of waste through efficient resource recovery and material reuse. When deconstruction companies dissociate themselves from demolition, the careful dismantling of buildings and structures – designed or not for disassembly – can create a supply chain channel for material suppliers to process, refurbish, and resell recovered elements or materials, with all the positive impact that this has on the system both economically and environmentally.

With the help of digital platforms, this relationship can go further beyond with data sharing that facilitates material traceability where material suppliers can track the lifecycle of materials they provide, enabling them to offer warranties or guarantees even on reclaimed products, and deconstruction companies can use data on the provenance and performance of materials to ensure that they meet modern safety and sustainability standards.

Financial Institutes and Insurance Companies

Through jointly supporting circular economy projects, financial institutions can provide capital to businesses adopting circular design through certain loans, funds, or sustainability-linked financing, where insurance companies could develop tailored insurance products to de-risk these investments, ensuring that circular innovations are protected from potential setbacks, and offer lower premiums to businesses employing circular practices, in line with sustainability commitments.

Both sectors can foster ecosystems that connect businesses, investors, and insurers to scale circular solutions. A company transitioning to a product-as-a-service model in building elements for example may secure funding from an institution and the insurer could step in to provide risk coverage for the extended product life, ensuring components remain functional and recoverable, thus supporting both financial and environmental sustainability.

By aligning their goals and leveraging their strengths, financial institutions and insurance companies can together reduce barriers to circular design and accelerate the transition to a more sustainable economy.

6.1.1.2.2 Conflicting connections mapped.

It is innate in any interaction for threats and conflicts to exist among stakeholders who have diverging interests or whose goals and actions do not align with the views of others on circularity or other related questions. In this study, four conflicting relationships were mapped from the data collected in the interviews with the expert contributors.

Building Owners (or users) vs. Business Developers

The potential conflict lies in the fact that business developers often prioritizing financial returns and rapid project completion, can resist additional costs or time investments needed which can sometimes conflict with the sustainability goals of building owners who might be looking for long-term benefits and more sustainable or circular construction practices. It mostly depends on who is the financial backer of the project in question, since this stakeholder is the one who has control and an be the party who will opt for less ambitious and lower-budget approaches that have a high chance of being the usual linear solutions whose externalities have not yet been priced in the business models adopted.

Despite this being a conflicting situation that creates barriers towards adopting regenerative circular approaches it can also be a driver through innovation that creates more affordable solutions than not and extends the focus towards economic elements as well. Going beyond the duality of the stakeholder relationship, *"We need to look at it much more economically than we do it now, we don't look at it economically, we look at it ecologically and that's all the calculations, all the purpose I see is around ecology in circular economy for the moment and then circular economy will not work.* (C3)"

Construction Companies vs. Insurance Companies

Insurance companies are naturally considered to be risk-averse due to their business models and therefore may be hesitant to cover new, non-extensively tested sustainable materials and construction methods, which can limit the ability of construction companies to innovate. This relationship can be fraught with tension particularly at innovation inflexion points where uncertainty levels tend to be high. This uncertainty makes it challenging for insurance companies to predict potential failures, liability issues, or long-term durability. As a result, they may stand on the side of caution, to the detriment of other stakeholders eager to use these materials. This, allied to the mounting pressure on construction companies to reduce their environmental and other impacts can become a retardant to innovation in design, materials, concepts, and even business models.

Material Suppliers and Manufacturers vs. Logistics Companies

The goals of minimizing costs and maximizing efficiency in logistics can sometimes overlook the sustainability of the materials being transported therefore end up not integrating circular material flows for economic reasons.

IT Providers vs. Construction Companies

Resistance to change in traditional practices can slow down the adoption of innovative solutions and digitalization that could drive sustainability. This might arise due to mindset and culture but can also happen because of costs involved and skilled staff available. As the built environment becomes more and more digitalized, its reliance on IT services becomes one more cost center to add to projects in general and adds one more skill that needs to be sharpened especially in a traditional environment as is the case for the construction sector.

In summary, the interview data points towards finding common ground through open dialogue to solve non-symbiotic relations. This involves goal alignment by reframing priorities to overlap benefits of different players in a way that no one is losing at the cost of another, and to recognize the long-term benefits of sustainable development creating a future vision that can be looked forward to. In connection with project CO2REDRES, this stakeholder mapping is an exercise that can be always viewed as a picture in motion in which every box of the matrix can be connected with one or more actions that bring two stakeholders together with a common objective. While thinking of a future of regenerative sustainability, "*every action matters and every connection is important to achieve the goals of a sustainable future. (B3)*"

6.1.1.3 The circularity policy landscape in Luxembourg

To analyze the ideas and insights generated throughout the interviews regarding local and national policy for circularity in the built environment, the starting point lies in looking at the existing policies in the country at both levels.

The approach to policy in this research through the interview questions formulation was an exploratory one to understand how stakeholders perceive it, i.e. what are their critiques of policies directed towards circularity, and what are the blind spots that these policies hold in context of the three ontological levels explained in the section Interview design of the research methodology.

The interviewees listed several policy instruments that are discussed in this section. It is important to point out that some participants considered policy elements as the equivalent to a Grand Ducal law, and indeed they would then consider that there is no such official policy that deals exclusively with circularity in the built environment as a specific stand-alone topic, but rather permeating some other policy documents such as strategies and certifications.

The results of this analysis are grounded in empirical data gathered through the interviews and documentary analysis of the referenced policies by the participants, ensuring a multi-angled and evidence-based approach to understanding the subject in the absence of a specific policy instrument exclusively related to circular construction materials. The interviews provided direct insights from participants, capturing individual perspectives and experiences, while the documentary analysis supplemented these findings by supplying objective data from the relevant documents. These two steps of analysis together enhanced the reliability and depth of the analyses and contributed to an interpretation aligned with the analytical framework described in the methodology section (the three ontological perspectives).

6.1.1.3.1 Laws, strategies, and initiatives as policy elements

The overlap in this section between the policies listed as a research result originating from the interview data and its broader content as a literature review format from post interview research is meant to create physical proximity in the analysis text rather than presenting those in different chapters. The content presented here is fruit of the interview data analysis, except where a reference is cited.

6.1.1.3.1.1 Null Offall Lëtzebuerg (2019)

As an initiative of the Ministry of Environment, Climate and Sustainable Development, this strategy document primarily aimed to provide the methodological foundations and a toolkit for translating the European Circular Economy Package directives and the Single-Use Plastics Directive into a new national law for waste and resource management. Having as a primary goal the elimination of the very concept of waste, the strategy seeks to support a paradigm shift from waste terminology to resource management, highlighting the value and quality of material flows and stocks present in daily life, thus focusing on 4 different themes that are key elements that were supposed to be used to develop the National Waste and Resource Management Plan, the PNGDR, but ended up succeeding its first version in 2018, and are therefore complementary texts. The four themes of this strategy are:

(1) Protecting and using soil, forests, and water better.
(2) Better use of products and services.
(3) Better packaging of products and waste reduction.
(4) Properly constructing and deconstructing buildings.

Themes 1 and 4 are of interest for the built environment since they address the issues related to spaces and structures, with the last setting specific objectives about certain circular ideas of how to (a) consider buildings as material banks, (b) encourage construction modes that avoid excavations and landfilling, (c) prolong the useful life cycle of buildings, and (d) create a market for deconstruction materials and elements. *"It provides you with some insights on* *what the future development should be, and gives some basic ideas to the implementations, but there's still further development needed (A1)"*

Some of the final specific recommendations and conclusions in the strategy document [336] align with what the interview data suggest around the cost of circularity as a barrier to the adoption of circular practices, and the high potential of reduction of waste in the construction sector that needs to be channeled through widespread applications involving all sectoral stakeholders.

The strategy tries in a way to point out to the possible synergies between the themes as well such as reusing and repurposing efforts that can be introduced into the construction sector though special repair, exchange and sharing centers with the objective of keeping materials and building components out of the waste stream. This can become achievable through stakeholder interaction as presented in the mapping chart in section 6.1.1.2 and reinforces the need for a design-level shift with circular concepts such as the shearing layers and design for disassembly and deconstruction, among other concepts discussed in the literature in chapter 2.

Part of the strategy's objective is also to begin shifting the linearity of local construction industry in every aspect to fall (not only for waste) in line with the EU circular policies, by starting to acknowledge the importance of digitalization as an essential medium that can assist in planning and providing transparency and traceability on material flows both quantitatively and qualitatively, as well as the question of producer responsibility and the challenges due to the long lifespan of built structures.

6.1.1.3.1.2 PNGDR – National Plan on Waste and Resource Management

Cited by some participants as a major policy blueprint with "*the aspects of circular economy are already in, with different measures* (A1)", this document was published and approved by the government in 2018 as a guiding document for waste management law updates and alignment with European legislative context and is centered around the benefits of waste reduction and elimination, including among other sectors the construction industry.

The measures described in the plan aim to improve waste management in Luxembourg's construction sector, with a focus on prevention, valorization, and effective landfill site management. This is a design concept based on the waste hierarchy concept described previously in the literature chapter (Figure 31)

Seen at the top of the inverted pyramid of waste hierarchy, the prevention of inert waste, particularly excavation soil, is considered a priority and has been the topic of an awareness campaign driven through the PNGDR. The prevention theme is the first of three categories addressed under the section related to the construction and demolition waste, it is also intersectional with the waste law of the 21st of March 2012, that has been modified posteriorly in 2022 and is also discussed in this section. The PNGDR refers to a database and a consultancy service on construction waste handling by the *Super Drecks Kescht* organism. The law requires waste prevention to be considered during the planning stages of construction projects, and an implemented database should help companies estimate the types and quantities of waste that will be generated.

After prevention, the topic is valorization and it involves encouraging the reuse and recycling of inert waste, with practices such as reusing excavated soil on-site and producing construction materials from inert waste, which circles back to the initial part of this thesis and project CO2REDRES doing exactly this by analyzing the feasibility of use of secondary waste materials as construction materials. The document also states that construction sites must implement the separate collection of different types of waste to facilitate their valorization, which is an important element for circularity, as one of the main obstacles to recycling is the way the construction and demolition waste is treated. This also reflects on new construction methods, since it would make designers and contractors think of the post-use stage of the life cycle, especially with extended producer responsibility concept surfacing into the debate in EU policy as discussed in section 2.2.7.2.

The third part is related to the elimination of waste and encourages initiatives like planned deconstruction and the highest possible recycling efforts prior to considering discharge sites as a solution.

Among the listed objectives of the PNGDR are the prevention of excavation of soil, encourage backfilling, the stabilization of valorization rates at around 90%, and a further promotion of the reuse of construction materials.

The plan does not really provide a detailed plan of what is to be done but rather refers to measures to be taken, but that still need further elaboration. Among those are the recovery of vegetation soil layers, the promotion of design for disassembly, and the higher levels of reuse of recycled materials in construction as well as sorting waste in projects on-site. It also slightly touches on material passports and the creation of a material stock market or marketplace.

6.1.1.3.1.3 PNEC - Integrated National Energy and Climate Plan

Luxembourg's National Energy and Climate Plan (PNEC) is the product of collaborative efforts across various ministries, coordinated by the Ministry of the Environment, Climate and Sustainable Development, and the Ministry of Energy and Spatial Planning, that got adopted in July 2024 in its final version after incorporating input from public consultations and institutional partnerships that were developed over the past years.

The main aspect is its role in shaping the country's climate and energy policy, outlining goals and strategies for 2030 across six sectors, most of which are intersectional with the built environment such as buildings, energy and manufacturing industries, construction, waste and wastewater treatment, and land use among others. Although these multiple sectors are related to the built environment, the document is mostly only related to energy aspects and greenhouse gas reductions through a strategy of pushing for a higher share of renewable energy input and use and better energy efficiency. According to the government, the targets to achieve climate neutrality, i.e. zero net emissions in 2050 and intermediately by 2030 reducing greenhouse gas emissions by 55% compared to 2005, achieving a 37% share of renewable sources in final energy consumption, and improving energy efficiency by 44%.

The PNEC does not address circularity per se but in its effort to support the energy renovation of the entirety of existing low energy performance buildings indirectly assists the sector towards extending the lifecycle of structures and thus contributing to circular design principles. It also addresses multiple financial questions such as the CO_2 tax as well as certain incentives and financing mechanisms, and how to invest in the energy transition that the country aspires to undertake. The part related to buildings is described in a couple of actions and can be grouped under key action categories related to (1) regulatory and policy framework for energy efficiency and decarbonization, (2) incentives and financial support programs, (3) strategic long-term planning, (4) training initiatives, and (5) public sector buildings leadership role.

The OPC (*Observatoire de la Politique Climatique*) with their emphasis on just transformation and systemic solutions, referred to certain critiques on the PNEC content in a specific report [337] calling to extend the narrow focus into "*integrated solutions of cross-sectoral relevance*" that "*transform systems and behavior away from unsustainable practices*" through a more just transition.

The Low-Carbon Construction Roadmap of Luxembourg (2023)

The Low-Carbon Construction Roadmap for Luxembourg, launched in 2023 aims to decarbonize the construction sector in line with the revised Energy Performance of Buildings Directive of the EU and the national greenhouse gas reduction targets set by Luxembourg's amended Climate Law of December 2020. As Europe moves towards mandatory embodied emissions calculations for all buildings by 2030, this roadmap seeks to establish an annual carbon budget for embodied emissions in new construction and renovation projects, expressed in $kgCO2\text{-}eq/m^2$. The other objectives include the assessment of current baselines and performance gaps using the European "Level(s)" framework and the development of decarbonization strategies that incorporate technological, regulatory, and financial innovations. The scope focuses on embodied emissions throughout the material lifecycle, covering production, construction, maintenance, and end-of-life stages. Key work packages include defining a carbon budget, creating databases for material inventories and Environmental Product Declarations (EPDs), developing a Life Cycle Assessment (LCA) methodology, and establishing decarbonization pathways. The roadmap sets the foundation for reducing embodied emissions in the construction sector, however, does not address circular economy in a direct manner, but rather through certain design concepts in the work packages described such as assessment of renovation works through LCA, and the construction material inventory database which is a pillar of a circular future for the built environment.

6.1.1.3.1.4 Pacte Climat

The Pacte Climat (Climate Pact) is a Luxembourgish program designed to strengthen the role of municipalities in climate and energy policies and it includes 79 measures divided into 6 categories. On the circularity aspect, it does encourage local communes to adopt measures aligned with the principles of the circular economy at different levels despite the focus on energy.

The program was updated in 2018 to include specific measures for a circular transition such as supporting modular and reusable design in buildings, promoting circular economic models such as shared economy and product-as-a-service, the adoption of sustainable procurement practices by focusing on certified materials and renewable local resources locally, and providing funding and technical assistance to implement circularity-focused projects effectively in local municipalities.

6.1.1.3.1.5 Circular Economy Strategy for Luxembourg 2021

This strategy document of 60 pages is dedicated specifically to circular economy and addresses the construction sector in a dedicated section. It acknowledges that the sector holds a pivotal role in advancing a circular economy due to its substantial economic impact, extensive material use, and high consumption of both direct and indirect energy. The vision for transition is centered around resource management, and the strategy aims to leverage tools like public procurement and material passports in collaboration with state and municipal promoters to push innovative practices into the market. The methods and tools described in the document are based on a framework that takes as a reference the resource triangle (similar to Figure 31) to classify those as actions that create, maintain, and recover value across three categories: regulation, finance, and knowledge creation and management. The described initiatives for transition encompass the adoption of bio-sourced materials, such as wood, to support climate goals by storing CO_2, the renovation of existing buildings to preserve embodied value, circular design methods like design for disassembly aim to minimize environmental impacts by enhancing reusability and resource recovery, circularity-based public procurement, material passports for traceability, and BIM methodology for cross-industry information management. The primary objective of this strategy document is to embed circular construction within urban planning processes, in a way that ensures that limited resources, such as land and biodiversity, are preserved and integrated within value-oriented spatial design, with some references to "*regenerative growth*" in the introductory section. Furthermore, comprehensive education and training programs are considered integral to the vision set by the strategy, with courses on circular principles extending from primary education to vocational training.

To date, there was no published follow-up of how each of the suggested methos and tool fared or if they were implemented and or their success measured. However, certain methods based on existent precursors such as LENOZ and PCDS (see section 2.2.6.3) and the sustainable construction guide are easily verifiable in the context of circularity in Luxembourg.

6.1.1.3.1.6 LENOZ certification for buildings

The *Lëtzebuerger Nohaltegkeets Zertifizéierung fir Wunngebaier* created by the law 23rd of December 2016 modifying the law of February 25, 1979 is a voluntary certification that introduces a financial aid scheme for property owners to obtain a sustainability certificate for housing and evaluates housing sustainability across six main categories, which include social, economic, ecological, technical, functional, and geographical aspects. These categories are further divided into subcategories called themes and each theme has several criteria that are evaluated. The relation of each to circularity is:

(1) *Geographical location* – evaluating the structure's integration within the urban context, its connectivity to social infrastructure, and site quality factors.

(2) *Social aspects* – looking at social functions within collective buildings and land usage.

(3) *Economic aspects* - evaluating energy consumption, focusing on cost-effectiveness and efficiency.

(4) *Ecological aspects* -having the most circular economy principles and includes (not limited to):

- Environmental assessment of construction materials, emphasizing sustainable sourcing and durability.
- Primary energy needs across the housing lifecycle to reduce long-term environmental impact.
- Wood resource evaluation, promoting the sustainable use of renewable materials.

- Water usage and wastewater volume, prioritizing resource-efficient design.
- Renewable energy utilization and self-consumption of electricity, aimed at reducing reliance on external resources.
- Energy-efficient appliances, which support lower overall energy demands.
- Integration of natural elements and revitalization of existing buildings, encouraging the use of natural surroundings and adaptive reuse to extend the life of structures, reducing waste from new construction.

(5) *Technical aspects* – *e*valuating building and technical installations, including sound insulation, thermal regulation, maintenance, and ease of assembly and disassembly (important for circular design).

(6) *Functionality:* considering comfort, air quality, safety, universal design, and pollution controls for occupant health.

(7) LENOZ is usually completed and complemented by other international certifications such as BREEAM and DGNB that also cover an extended set of details and different methodologies that are not the main focus of this data analysis but are worth noting (see section on standards and certifications 2.2.6.4).

6.1.1.3.1.7 Fit 4 Sustainability program

The program in Luxembourg is a structured initiative by Luxinnovation and the Ministry of Economy designed to assist businesses in transitioning to more sustainable practices. The program has a diagnostic and an implementation phase. The first phase lasts up to six months and aims to analyze the situation of the consulting business in terms of sustainability. It provides an assessment across three main metrics, including decarbonization e.g. carbon footprint and energy audit, water e.g. consumption, and circularity e.g. LCA. Based on current standards and regulations, the assessment identifies areas for improvement and suggests measures to reduce the business's environmental impact. The phase concludes with a comprehensive report detailing potential solutions, the legal framework for aid, necessary permits, environmental and cost-effectiveness analyses, and a financial forecast. Afterwards, if the business opts to proceed with the diagnostic recommendations, they may still be eligible for further subsidies.

6.1.1.3.1.8 *The waste law: Grand Ducal Law of 9 June 2022 modifying the law of the 21 March 2012*

The modified waste law of the 9 June 2022 and in specific article 26 regarding waste management in construction and deconstruction is based on the principles of prevention with a waste hierarchy concept described in the *Null Offall* strategy, responsible waste management systems, and facilitating collection, sorting, and reuse as well as digitalization. The main points related to circularity in the built environment are:

- Waste Prevention and Reuse: At the planning and contracting stages of construction, minimizing waste and promoting reuse is made mandatory. Project owners must demonstrate these prevention efforts if requested by authorities, and measures must be taken to avoid contamination of recyclable materials, particularly separating hazardous materials from non-contaminated materials, and sorting waste by type in general for selective collection. In addition, the law states that regulations may establish quality standards for recycled construction materials based on their intended use.
- Enlarged Responsibility for Municipalities: They must provide separate collection facilities for small quantities of construction waste from private individuals, with appropriate recycling and disposal options.
- Role of the Public Sector: The reuse in public tenders of inert materials in construction projects is mandatory.
- Inventory for Deconstruction: Prior to the deconstruction of any building with a built volume exceeding 1,200 cubic meters and generating at least 100 cubic meters of waste, the owner is obliged to compile a comprehensive inventory identifying the various materials used in the structure. For larger deconstruction projects, where buildings have a built volume of 3,500 cubic meters or more, this inventory must be carried out by an approved organization.
- Digital Registry for New Buildings: For new constructions over 3500 cubic meters, a digital registry of materials must be created for permits issued from 2025 onwards and kept up to update by the property owner after completion ensuring traceability and supporting future recycling or refurbishment efforts.

Other parts regarding road infrastructure and landfill location and use are also addressed in the law text.

In comparison to EU law, this legislation transposes key directives such as the Waste Framework directive and especially the notion of waste hierarchy which is supposed to give preference to prevention over recovery over disposal and strengthens the extended producer responsibility concept. The special part that is of interest for this research is the requirement of inventories and separate collection of construction materials to facilitate recycling, in line with EU directives promoting material recovery in the construction sector.

6.1.1.3.1.9 Other policies not cited in the interview data

Since the data analysis was based on the interview data as described in the methodological considerations chapter, some of the existing policies or those that have been announced posterior to the data collection phase are not present in this analysis due to either the temporal factor or the participants' personal considerations on what constitutes CE policy and where to draw the line with respect to that. To this end, some complementary national and local policies that illustrate the extents of CE concepts embedded in policy is presented in the annexes (Annex 3).

6.1.1.3.2 Perceptions on policy for circularity

Policy can be distinguished at two levels in Luxembourg: the national and the local. Policymakers at every government level play a crucial role in facilitating the transition to a circular economy by creating the necessary legal framework for the transition, building financial structures that directs capital towards circular initiatives, involving stakeholders into the conversation on sustainability, and fostering innovation and research. On the local level, communal administrations can simplify processes to encourage a vision that is centered around regenerative circularity and embed circular economy principles into their projects and administration. These ideas reflected by the participants' points of view are mostly in line with what is generally in policy recommendation studies however, they do diverge on certain points and agree on others. These tensions are presented and explored in the next sub-section.

6.1.1.3.2.1 Points of agreement

Need for Regulatory Support. There is a consensus among most contributors that stronger regulations are required to promote circularity in the construction industry. Many of the interviewed experts believe that without helpful and consistent regulations, market forces alone are insufficient to drive significant change. In this sense comes the call for strong regulation that guides the way towards transition, but contrasts with strict and constricting regulation.

Importance of Material Passports. Several of the experts agree on the importance of material passports as a tool to support circularity, although they note that current regulations are inadequate or poorly enforced in this regard and have yet to adapt to the built environment products and materials.

Challenges with Implementation. There is a shared concern about the complexity and efficacy of current policies. Certain contributors expressed having the impression that policies or policy elements exist in theory but are either poorly implemented or lack the necessary enforcement mechanisms, while others such as the Lenoz certification is deemed complex and costly. There are no numbers or measurements that confirm this on a wider level, but it is a recurrent theme among interviewed experts while discussing about national policy.

Role of the Private Sector in Influencing Policy. Experts acknowledge that the private sector plays a key role in shaping policy in Luxembourg, often being involved in the consultation efforts run by the public authorities prior and during the drafting of regulations. However, there is concern that this involvement may lead to regulations that are more favorable to business interests than to circular economy principles, especially that not everyone participates. It is often the big players that can afford time and resources to carry out incremental activities besides their core business, while smaller players have to focus on the day-to-day business and don't always engage in such conversations.

Waste Management as a Key Focus. There are converging views that current policies are heavily focused on waste management, though this is seen as a limited approach to circularity as discussed in the literature chapter. The idea of downcycling (e.g., using rubble in base layers of roads) is criticized as insufficiently circular, and that even with the end of waste criteria coming from the latest law changes, the level of circularity is not yet as complete as it could be, lacking a more inclusive approach that includes social aspects and a more holistic vision of circularity that goes beyond waste management.

6.1.1.3.2.2 Points of divergence

While there is broad agreement on the need for circularity, the exact path forward is subject to debate. Some advocate for a regulated, top-down approach where the government plays a more active role, while others believe in market-driven solutions with minimal regulation but strong incentives.

Effectiveness of Current Strategies. When it comes to policy there is a split among experts regarding the effectiveness of existing strategies and guidelines, particularly those related to waste management. While some see these as positive steps towards advancing the circular economy, others argue that these strategies are too vague or insufficiently enforced to drive real progress. This disagreement highlights the need for clearer definitions, more robust implementation, and better enforcement of policies. The challenge lies not only in having the right policies but also in ensuring their practical application in the construction sector. This is further detailed in the section on *policy hindering elements*.

The Future of Circular Economy. Experts also differ in their outlook on Luxembourg's progress through circularity. Optimists point to various initiatives and new projects as evidence that the country is on the right path, while critics argue that Luxembourg lags behind other European countries and needs to take more ambitious steps. Those who are critical often point out that while small improvements are being made, the overall approach tends to focus on short-term fixes rather than a comprehensive rethinking of the entire construction and waste system and the policies that regulate it.

Market vs. Regulation. A key disagreement revolves around the balance between market-driven solutions and government regulation. Some argue that the market, through financial incentives and innovation, can effectively drive the transition to a circular economy. They believe in encouraging businesses to adopt circular practices by reducing taxation on reclaimed materials, for example, or offering subsidies for sustainable innovations. However, others assert that the market alone cannot be trusted to achieve circularity, and that strict regulations are essential to ensure compliance and fairness across the board. This group supports stronger regulatory frameworks to force the adoption of circular principles.

6.1.1.3.3 Policies in context

Having explored the national and local policies that were mentioned in the interviews as tools and strategies linked to circularity in the built environment in Luxembourg, more specifically in the context of the construction industry, it is essential to delve deeper into their relationships with broader EU directives, identify their potential relation to material circularity and SCM tying to project CO2REDRES, and examine their ontological aspects focusing on the conceptual underpinnings, i.e. how they define and address waste, sustainability, and circularity.

To facilitate this analysis, the following table (Table 30) presents a structured overview of the described policies. It categorizes each policy by its key features that can relate to project CO2RERDRES, alignment with EU laws and relation to circularity in the built environment, and the ontological dimensions it addresses.

Table 30. Policy in context of the different ontologies

Policy document	*Relation to EU policy and context*	*Relation to circularity in the BE*	*Relation to material circularity and SCM (CO2REDRES)*	*Positivist ontology*	*Social constructivist ontology*	*Pragmatist ontology*
Null Oufall	National context in relation to PNGDR. Aligned with EU Circular Economy Action Plan. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste	Theme 4 on buildings (buildings as material banks, decreasing excavation, prolonged structure lifecycle, secondary materials market)	Section 4.2 on excavation limitations: "*Promote and support initiatives for reusing excavated soil, … exploring innovative techniques such as transforming it into useful construction materials*" given that the excavation materials are clay based for use as SCMs. Section 4.4 on markets for deconstruction materials: *"Launch and support demonstration projects for the reuse or repurposing of materials and components in Luxembourg, integrating on-the-ground experience.*" Which could also be the case for valorizing waste and industrial byproducts as substitutive raw materials	Present Positivist tendencies with a data-driven approach to resource management, BIM, LCA, etc.	Partially present In the roadmap description certain social aspects including communication and raising awareness are an acknowledgment to the importance of social context for transition.	Partially present Pragmatist tendencies are limited but not absent, stakeholders are identified and initiatives creating synergies between actors as well as market initiatives are stated in the roadmaps that are suggested. Workgroups and collective experiences are seen as part of the solutions that can embed circular design concepts into the built environment especially through creating and learning from pilot projects and fostering innovation.

			as well like in project CO2REDRES.			Moreover, considering the financial aspects, and social ones beyond the infrastructure is an indication of policy looking at the broader picture.
Circular Economy Strategy for Luxembourg	Aligned with EU Circular Economy Action Plan. Mentions tackling economic cycles at the level of the Greater Region, in collaboration with neighboring countries and the EU.	Section 5.2.1 on construction	Recovering value propositions in key circular tools proposed – *"Developing a regulatory framework for the reintroduction of recovered and recycled materials, components and products in the construction market"* while the focus would be on recovered materials, it could well extend beyond and include industrial by-products that have been tested as SCMs at least for nonstructural elements until standardization has advanced. Under financial aspects *"Explore incentives adapted to the reuse of recovered and recycled*	Present Incorporates quantitative elements (e.g., tracking materials via material passports, adopting EPR policies).	Present Although grounded in practical applications, still mentions social inequality, education, training, and community aspects, acknowledging that success depends on shared social values.	Present Presence of action-based methods—such as embedding circular practices in procurement, urban planning, and public-private collaborations—all indicators of a pragmatic approach to enacting circular economy principles. Interdisciplinarity is seen in approaches that promote cross-sector engagement, and stakeholder collaboration. With the strategy referring to *"a regenerative growth model that gives to the planet more than it takes"* it

			materials, components and products in the construction sector." This could also be a strategy to create incentives for use of SCMs, that so far doesn't exist neither for the traditional SCMs that are already used since decades, nor the new ones being researched.			takes a step ahead in principle with the holistic and regenerative view on circularity , although it is still connected to growth as in traditional economic theory.
Pacte Climat	Directives EU (2010/31, amended by 2018/844) Energy Performance of Buildings Directive (2018/2001) Renewable Energy Directive (2008/98) Waste Framework Directive EU Circular Economy Action Plan Nationally, aligns with the Grand Ducal climate law 15	Established a framework to support the climate goals of Luxembourg through municipal level action to achieve climate neutrality by 2050	With a 0% emission objective until 2050, this could entail a better inclusion of strategies beyond energy and into material technology, and using green concrete for example with SCMs or other material technologies that are researched and developed for the reduction of clinker content.	NA	NA Promotes sustainability as a shared goal and to some extent recognizes the success of measures depending on their integration into the social fabric.	NA Has some pragmatist elements that arise from its structure of giving local communes a leading role in change and the structure of stakeholder participation and sharing of good practices, actionable solutions, and prioritizing action and tangible results. A great example is the creation of the circular hub in the commune of Wiltz as a testing space.

	December 2020 and the PNGDR					
PNEC - Integrated National Energy and Climate Plan		The PNEC essentially translates the European directives and national legal frameworks into actionable strategies to ensure Luxembourg meets its climate, energy, and circular economy goals.	Does not refer to materials – as it is related to energy mostly so the connection to SCMs is minimal or indirect.	Present Mostly related to the policy framework on energy efficiency and phasing out fossil fuel heat systems in buildings, mandatory energy renovations, etc.	Partially present Focus is on energy efficiency. However, certain aspects of public and community support such as awareness, information, and consulting services and assistance for households facing energy poverty are mentioned.	Not present Focus is on energy efficiency.
PNGDR – National Plan on Waste and Resource Management	Intersectional with the Grand Ducal Law of 9 June 2022 modifying the law of the 21 March 2012 concerning waste and all the EU policies related to it.	Section 3.7 specifically on construction and demolition waste	With a focused approach on waste prevention, valorization, and ways of elimination, it is restricted in scope to construction and demolition waste and does not address secondary waste materials or by-products from quarries or raw material extraction such as the ones studied in project CO2REDRES.	Present Relies heavily on empirical data approaches such as the use of statistical tracking for recycling rates and scientific criteria for landfill site selection, as well as an approach aligned more with waste management rather than resource	Not present The focus is on waste as a standalone item.	Not present The focus is on waste. Notions of circular design such as design for disassembly is mentioned but does not offer any details on implementation measures or strategy.

				management. Material passports and inventory are also a present topic.		
LENOZ building certification	Grand ducal law 23rd of December 2016.	National sustainable construction certificate primarily based on energy performance but having certain categories (themes) related to circularity such as design for disassembly, surface use, and refurbishment of existing buildings or spaces among others.	The certification does mention the role of materials in achieving sustainable construction but more from the quality and environmental impact assessment sides, which can relate to the use of SCM. Although the use of SCM is not the focus of the certificate's scope it still can establish a relation with such material technologies and concepts by considering them as sustainable alternatives to OPC concrete.	Present The framework focuses on measurable ecological aspects with energy efficiency at the center but is not limited to those and certainly not detached from the social context that the structure is embedded in.	Present Through evaluating housing in terms of social integration and community impact, the certification scheme reflects on societal values and norms around sustainability and collective responsibility in a way (fair social organization).	Partially present Offering financial aid to owners who improve the sustainability of their housing and trying to address categories beyond energy and water, that can create practical solutions can figure as a pragmatist approach. Nevertheless, it is not a protruding facet of the certification scheme.
Fit 4 Sustainability program (not a policy but part of the circularity landscape strategies)	Joint program by the Ministry of Economy and Luxinnovation	Applicable if a consulting business is in the construction sector	It might be possible that certain solutions proposed for construction companies could be related to the use of SCMs but it still is depending on the solutions being mainstreamed into industry and covered by	Present Technical assessments such as energy audits, resource consumption and LCA for example, seek objective solutions that aren't	Absent (conditional on outcome) By tailoring the solution to each business and taking into consideration the social context of sustainability	Absent (conditional on outcome) At implementation phase if it succeeds to be an action-oriented program to solve real-life problems through

			standards and industry norms, which is a step ahead of the present reality in which the use of SCM is.	grounded in any social context, but rather a more universal approach of quantification.	without a one-size-fits- all approach, the program could embody social-constructivist ontology if the consultants look beyond the initial framework, reflecting an understanding that context influences how sustainability strategies are applied.	assessing sustainability issues holistically considering dimensions beyond business benefit, and co-creating solutions with relevant stakeholders it might be considered pragmatic. However, given the three-layer framework of decarbonization, water, and circularity it is unlikely to cover the broad range of impacts that businesses realistically create or produce.
Low Carbon Construction Roadmap	Aligned with the EU directives 2010/31/EU on the energy performance of buildings and 2023/1791 on energy efficiency	Not related to specifically but there exists a connection to circularity regarding material inventories, renovations, and digital approaches in general in some of the work	Dependent on the incorporation of ways of decarbonization by achieving substitution targets of OPC with SCM as parts of the strategy.	Present Primarily related to carbon emissions and quantification through LCA and EPD. There are certain connections to the *Guide to Sustainable*	Not present The highly technical nature of the roadmap does not exceed beyond engineering and environmental aspects.	Not present Although very outcome focused, the nature of the document is very connected to carbon emissions, however certain stakeholders are included in the discussion.

		packages presented.		*Construction and Renovations by CRTI-B*		
Grand Ducal Law of 9 June 2022 modifying the law of the 21 March 2012 concerning waste	Aligned with the Waste Framework Directive 2008/98/EC, the EU Circular Economy Action Plan, and the EU Construction and Demolition Waste Protocol At a national level related to the PNGDR.	With a specific article on construction, it adds slightly more stringent requirements than EU policy such as the compulsory digital material tracking, municipal support for construction waste separation even at individual level, and mandatory reuse in new public projects.	The connection to project CO2REDRES is present in the general sense of the content since it is a law that regulates waste and despite the absence of references to SCM the general context leads to developments in using the entirety of extracted or excavated materials and avoiding landfilling as a solution.	Present The law text provides a positivist perspective, aligning legislative requirements with tools such as material inventory, optimizing waste separation, recycling, and material management all of which are not fully circular practices.	Not present The law only addresses waste in the technical context and definition without considering social and cultural factors that influence building practices, although starting a shift towards seeing and considering waste as a resource in the sectorial context is already a step towards changing the understanding of the waste-resource paradigm.	Not present The law is an improvement of the previous laws in the right direction with the introduction of waste as a resource but still does not transcend the idea of waste reduction into a regenerative perspective.

6.1.1.3.4 Policy hindering elements

A major obstacle to circularity policy in Luxembourg lies in the interconnectedness between single buildings and related infrastructures. There is a concern from some interviewed experts that circularity in individual buildings alone is insufficient if broader urban development trends—such as car-oriented designs or rigid neighborhood organization—remain unchanged. They express skepticism that single-building circularity can be the solution if developments continue to ignore integrated approaches to infrastructure. They suggest that circularity should be seen in combination with other concepts like shared spaces and flexible, multi-purpose building uses, which are largely absent from current urban planning and regulations in Luxembourg.

"If you don't think in combination, with mobility with sharing spaces that offer flexibility for multi-purpose users of buildings…all the material efforts are probably not sufficient to turn this into something more. (C2)"

"If you see that lack of changes in the general idea of how to conceive new neighborhoods or how to organize cities or towns in Luxembourg, I don't think that circularity of single buildings can be the solution. (C2)"

Another major policy barrier relates to the waste law and the classification of materials as waste. When excavation material, for instance, is categorized as waste under current regulations, it severely limits what can be done with it. Certain participants called for reforms to waste definitions to enable easier reuse of materials. They assert that regulatory frameworks have not been updated to reflect modern circular economy practices, which is crucial for encouraging reuse and avoiding unnecessary disposal. "*For example, the excavation material is always considered waste because of the regulation.*" And *"When we define something as waste, how you know once it has the status of waste, what can you still do with it? (B1)"*

In addition, regulation is seen as either too strict or too weak to foster innovation. Policies have not adapted to account for contemporary challenges that were not fully anticipated 10-20 years ago. A somehow outdated regulatory framework, coupled with a general business model focused on growth, limits the potential for systematic change towards circularity creating structural barriers that transcend policy. "*Sometimes regulation is not strong enough or too strong to let the open door to innovation. (A2)*"

A broader critique is aimed at Luxembourg’s economic model, which prioritizes growth over sustainability. Circular strategies are seen as coping mechanisms to handle externalities of growth, rather than being adopted as alternatives to continual growth. This growth imperative often leads to practices that are inconsistent with the long-term goals of circularity. *“It's more about all those strategies are more about coping with growth imperatives than thinking about alternatives to continue growth. So, just treating the externalities in a way. (C2)”*

Taxation policies add another layer of difficulty. Reclaimed materials face double taxation, discouraging their use in favor of new materials. These economic disincentives make reclaimed elements less financially attractive, despite their potential for reuse. "*There's also the taxation that is not helping because why having a second taxation on reclaimed elements. (A2)*"

Furthermore, deconstruction is often driven by the need to meet changing public standards, which leads to frequent replacement of building materials and components despite their usability. An example cited is the difficulty in reusing materials such as second-hand solar panels, which are *“supposed to last thirty to forty years and often changed after fifteen years (A2)”* but end up being exported and are ineligible for subsidies in Luxembourg. This leads to inefficiencies where perfectly functional solar panels are exported rather than reused locally.

Another critical issue in policy implementation is the unintended complexity arising from conflicting or overlapping regulations. When one law imposes restrictions while another allows the same or similar activity, individuals and organizations are left in a state of uncertainty and application becomes ambiguous thus translating into barriers to action as described by an interviewee *“… these are the hidden the obstructions. (A1)”*

Table 31: Blind spots in circular policy applied to the built environment in Luxembourg.

Policy document	*Blind spots identified related to circularity in the built environment (built up from interview data related to policy analysis and ontological classification review)*
Null Oufall	Overemphasis on individual action without addressing systemic inefficiencies in production and waste management, or even the prevailing mindset around sustainability.
Circular Economy Strategy for Luxembourg	Overlooks certain sectors that could benefit from circular models, but within the construction sector lacks a robust framework for tracking progress and evaluating or measuring the impact of suggested circular economy actions.
Pacte Climat	Prioritizes immediate climate and energy goals but lacks a long-term vision for deeper circularity integration.
PNEC - Integrated National Energy and Climate Plan	Not analyzed for blind spots – but generally overfocuses on energy production and is heavily dependent on tech-centered solutions without addressing inefficiencies in energy use in sectors like construction.
PNGDR – National Plan on Waste and Resource Management	The incentives provided by the plan are not extremely clear, and the related regulation is complex according to interviewed experts.
LENOZ building certification	A certain perceived complexity although already representing a limited scope that doesn't delve deeper into circular design, and a lack of post-occupancy performance that can verify or optimize building performance after certification.
Fit 4 Sustainability program	No data from interviews or analysis for such an evaluation, as it is project dependent.
Low Carbon Construction Roadmap	Takes Lifecycle Analysis with very high emphasis which might overlook other important venues to achieving carbon reduction through systemic transformation while not acknowledging the limits of such analyses.

To address the blind spots in Luxembourg's sustainability and circular economy policies in the built environment (Table 31), the data analysis suggests that certain improvements can be implemented. First, enhanced data collection and monitoring systems are essential to track progress, identify gaps, and inform evidence-based decision-making. Additionally, increased financial support and incentives for businesses and municipalities can encourage innovation and adoption of circular practices, fostering widespread participation from even smaller players who could not afford major change implementation otherwise. A stronger integration of systemic, cross-sectoral approaches is crucial to address interdependencies and ensure that solutions are scalable and effective across different industries and regions. Furthermore, active public and wide stakeholder engagement is necessary to build trust, ensure inclusivity, and secure broader acceptance of circular economy initiatives.

6.1.1.3.5 Policy Landscape Summary

Historically, the transition towards sustainability in the built environment and the construction industry in Luxembourg has been shaped by two distinct policy approaches according to *Preller* [338], namely green growth and social housing with urban sustainability. The two approaches align with the findings of this research on the policy spectrum ranges from techno-centric to holistic circularity and create a tension in Luxembourg's transition. The first approach aligned with a green growth agenda, is heavily present in current policy as seen in the analysis, and focuses mostly on energy efficiency and eco-technologies, pushing environmental goals to meet economic growth through technical solutions with key stakeholders such as the government and private developers promoting sustainability and circular solutions in a way that supports continued economic expansion. On the other hand, the urban sustainability approach prioritizes deeper societal changes, focusing on quality of life, and land use as responses to limited natural resources. While it promises more transformative change, this agenda has faced challenges in implementation and lacks the visibility of green growth initiatives.

From that background, and by looking at the interview data, the policy landscape for circularity in the built environment in Luxembourg, seems currently fragmented and underdeveloped for the ambitious objectives it embodies. While there are strategies and initiatives in place, such as the LENOZ certification and the national plan on waste and resource management (PNGDR) as examples, these are often seen as insufficient or poorly enforced. Key policies include the waste law, which mandates a hierarchy of waste treatment and has recently begun to include provisions for material inventories in large buildings. However, these policies are sometimes criticized for being reactive rather than proactive, and focusing on waste management rather than comprehensive circularity.

In summary, while there is a growing awareness of the need for circular economy practices in the construction industry, the existing policy framework has room for improvement, just like mentioned earlier in this section. There is a call for more transition friendly regulations, better enforcement, and greater alignment between public policies and market practices to drive the circular economy forward in a meaningful way. On top of that, analyzing the data further while discussing policy, a trend reveals itself with experts emphasizing the necessity of aligning goals among stakeholders and viewing regenerative practices as positive change. All this feeds into an important aspect which is how to reframe policy to capture value and push transformation forward. Despite not being explicit in the data, the very nature of thinking about shifting focus from isolated interventions to integrated solutions leads the way towards systemic transformations that create spaces that allow for reframing policy goals which is something that is needed.

6.1.1.3.6 Measuring circularity and the link to policy

The interview data presents a direction that points towards an importance of measurement and or evaluation in implementing circular economy strategies, particularly in the construction sector, and in policy related topics. The contributors generally emphasized that measuring outcomes such as embodied carbon reduction, material reuse, or recycling rates are crucial for understanding the effectiveness of policies and adjusting them if necessary. However, they also cited the challenges associated with data collection, access, and interpretation. There's a need for clear goals and indicators to measure progress effectively, but caution is advised against overly relying on metrics that may not fully capture the qualitative aspects of circularity, especially when talking about more holistic approaches that transcend the technocentric understanding of circularity. Moreover, collaborative approaches and stakeholder engagement are seen as essential in achieving broader circular economy goals, and those cannot really be measured in conventional quantitative ways.

Thinking back to systems, and if one perceives policy as an element of a wider system in place – the simple idea of feedback can be understood as the flow between different elements of this system as they interact through their connections and propagate the effects from one node to the other all the way from input to output. Now transporting this to policy, parallels can be drawn between measuring outcomes and the definition by *Norbert Wiener* of circular causality of a feedback loop, borrowed from the field cybernetics [339], where he states that a machine needs to be controlled based on its actual performance rather than its expected performance. Hence, the importance of the idea that the policy "machine" should be controlled and adjusted based on measured output rather than expected outcome. It is not uncommon that certain policies do not achieve their desired outcome or do achieve opposite or complementary outcome *"as some policy in one field* *might affect completely another filed without initially planning to (positively or negatively).* (A1)".

The need for comprehensive evaluation and monitoring has also been one of the outcomes of a research project by *Hild* [340] which identified a lack of systematic evaluation and monitoring to assess how circular practices contribute to sustainable development in Luxembourg, considering it challenging to measure the effectiveness and sustainability of implemented circular economy strategies, just similar to what the interview data suggested.

6.1.1.3.6.1 The importance of measurement according to interview data (in and beyond policy)

Adapting Policies Based on Performance Data

Measuring the effectiveness of circular policies is essential for several reasons. Firstly, it helps determine whether a policy is working and allows for necessary adjustments. "*For example, we make critical regulations for, let's say, recycling of road infrastructure, of road materials. There is a procedure given, and [then] you see how much it is used. It's a metric to measure how successful this regulation is. The statistics are very important for us to know, to have this feedback. Is it working or not? If it's not working, we have to adapt it or to make changes. (A1)*" This highlights the importance of monitoring policy performance and the role of data in guiding policy adjustments.

Ensuring Accountability and Preventing Greenwashing

Measurement provides feedback, accountability and transparency, helping to prevent greenwashing and ensuring that policies lead to genuine environmental benefits. "*It's important to measure where it should be, and it's the only way to prevent greenwashing or to see if you're going in the good direction... Of course, in the beginning, maybe it's more about data, and after you improve it, but should be transparent. (B3)*"

Capturing Broader Economic and Social Impacts

Furthermore, measuring circularity helps in understanding the broader impacts of policies, not just on environmental goals but also on economic and social outcomes. *"So how can a* *building that goes for local sourcing of resources incentivize new markets for local craft firms, new ways of valorizing resources? So how do the general production systems change? That could be another impact analysis*. *(C2)*" This shows how measurement can capture changes beyond mere material use, reflecting broader system transformations.

Enhancing Policy Effectiveness

Lastly, measuring the effectiveness of circular policies is seen as vital for setting future goals and ensuring policies are targeted effectively. "*There's no kind of systematic monitoring changes used in the building sector, and this could definitely help in also defining future goals and provide some accountability for that. (C2)*"

These insights emphasize that without proper measurement, policies cannot be effectively managed, improved, or justified, and their broader impacts on society, the economy, and the environment may remain unclear or underappreciated.

6.1.1.3.6.2 Key aspects in measurement of circular policies

Before effectively measuring the impact of circularity, it's crucial to define the specific goals. And usually, policies are by nature specific and oriented, however circular economy strategies can achieve a wide range of objectives—from "*reducing emissions and environmental impact to enhancing independence from global supply chains*. (B1)" However, participants in general converge around the existence of a gap in explicitly defining these goals, and that this lack of clarity hinders the ability to establish meaningful indicators to measure progress. Therefore, setting clear objectives and corresponding metrics is essential to determine whether adopted practices are genuinely circular and aligned with their intended outcomes. The key aspects cited as important to be measured can be grouped into the following clusters.

Material Use, Reuse and Recycling Rates

Measuring how much material is reused or recycled helps assess policy effectiveness, since *"…recycling rate of materials is a metric to measure how successful a regulation is. (A1)"*

Furthermore, *"a more traditional kind of impact analysis, [of] what sources have been used, what resource have been substituted, what energy gains could reach under, so this kind of more material analysis. (C2)"* contributes in a way to understand the impact of policies that promote these practices.

In contrast, other interviewees criticized the fact that recycling rate is an actual metric, creating a connection back to the definition of circularity and how each person perceives it. *"So, we measure, for example, the recycling rate. Well, that's a linear approach. So, the R [recycle], that we would like to get rid of is the key indicator of circularity today at the macro level. (C3)"*

Embodied Carbon and Environmental Impact

One way of ensuring the alignment to climate goals set in the adopted policies is measuring the environmental impact, including embodied carbon in construction materials, as noted in one of the interviews *"…you have to use depending for instance when we have now our objectives on climate neutrality that 20 or 30% of the buildings have to store CO_2 in some ways, or biogenic or another innovative material (C1)"* which suggests that certain measurements beyond emissions and economic feasibility can also provide good feedback for policy and decision making.

Adoption and Uptake of Circular Practices

The rate of adoption of circular practices could be one measurement to be analyzed by tracking the use of new practices described or not in policies. It can possibly provide insights into the path that practitioners are following and on policy uptake if it is a specific element. Doing surveys beforehand is a way of evaluating which policy elements are likely to be successful or adopted *"a survey beforehand… just to know what the companies are using… or just to ask if they are aware of the new law for example… simple, but many* people are not aware of it. (A1)"

Wider Economic Metrics and Resource Efficiency

Assessing resource efficiency, such as material use relative to economic output, can help gauge circularity better than other metrics inspired from linear economy, in some of the participants' opinions. As one interviewee puts it *"Why don't we look at the kilogram consumed per GDP created [instead of recycling rates]? (C3)"*

Such approaches offer a connection between multiple aspects that link circularity to other broader outcomes. "*I think there's two steps to this because otherwise simply measuring did we get more circular and measuring did we reach our goals, for me wouldn't be sufficient.* (B1)" because one cannot directly establish if there is a correlation for example between "*becoming better in terms of reducing greenhouse gas emissions or becoming more circular. (B1)*"

Impact on Business Practices

Some interviewees considered that measuring how circular policies influence market dynamics and business models is important, for examples *"…how can a building [or a project] that opts for local sourcing of resources incentivize new markets for local craft firms, or new ways of valorizing resources* (C2)" to develop in the market, *"and how does the general production systems change?* (D2)"

Behavioral and Systemic Changes

Understanding shifts in mindsets, routines, and networks among firms is another aspect that can be referred to while looking into the magnitude of change that circularity can achieve, as the data suggests *"…to what extent building practices or projects have changed or contribute[d] to changing routines, mindsets, attitudes and relationships and networks between firms?* (C2)"

Moreover, gathering qualitative feedback can help capture the broader impact of policies beyond technocentric metrics alone. The question raised is *"…do we need numbers, or can it be more qualitative? I don't think that there's one [answer]. The problem is I think in general with such systems… we are just measuring, counting, monitoring and then nothing happens* *with that... the more interesting part is what we are doing with it. Do we try to understand where does it come [from]? What is behind? (B2)"* These questions align with a systems approach because they address the basic principles and their connections to tools and methods of measurement. By asking such questions, awareness can be raised through the means of framing, designing, and evaluating for systems change.

6.1.1.4 Material technology

This section addressed three questions that were inspired strictly from the outcomes of project CO2REDRES and the challenges that were faced beyond the technical aspect of experimental laboratory research on sustainable building materials and material concepts, which connects both quantitative and qualitative approaches.

6.1.1.4.1 Sustainable materials in the construction industry: the status quo

While the construction industry faces increasing pressure to shift from traditional materials towards more sustainable and circular alternatives, certain material technologies hold good promise for reducing the sector's environmental impact, however, widespread adoption remains slow. The interview data reveals several factors that are possible explanations as to why the construction industry has not comprehensively adopted new, innovative, or even simply more sustainable materials, despite their promising performance and confirmed technical feasibility. One of the primary reasons cited is the industry's focus on scalability and volume. For non-traditional materials to be commercially viable, they need to ideally be produced on a large scale to meet the high demand of the construction sector and create profit. However, achieving this scale has been difficult due to the additional steps and costs involved in producing these materials. As one participant points out, "*...the industry wants masses, volume, volume, and then for the process to get to this volume, there is an economical factor because you have to treat the material, that is the main issue for them. (A1)"* While the technology exists or can be developed, the infrastructure required to produce these materials at the volumes needed for large projects is not yet economically efficient.

A second major obstacle is resource availability. This was one of the challenges with CO2REDRES scaling efforts, as the homogeneity of secondary materials as well as their available quantities are not always guaranteed. Many of the considered sustainable construction materials, and particularly those used to replace traditional cement, are derived from SCMs, which are often limited in supply as "*the base material to make these SCM materials is limited and if there is some scarcity of that material, they have to drive the (re)search for another one, so it's yet another process. (A1)*" This resource limitation complicates the adoption of alternative and sustainable materials because companies are hesitant to rely in their processes on materials that may become scarce or more expensive in the future. The need for a continuous search for alternative resources creates uncertainty, making it more difficult for businesses to commit to using these materials on a large scale.

In addition, the economic model structure upon which the construction industry is built on presents additional challenges. The sector operates high infrastructure investments as they have *"the sunken costs... and it's difficult to displace because they've invested on the machinery, everything is in place, to open, to operate, to have permits and everything. (D2)"* companies are reluctant to invest in new materials unless they offer clear financial advantages as discussed in length in the section on barriers for circularity. While sustainable materials may offer long-term environmental benefits, they often come with a higher upfront cost due to the need for new production processes, material treatments, and supply chain adjustments, and "*[the companies] can't change their production processes every five years or 10 years, then they go down.* (A2)". This suggests that the higher initial costs of implementing change discourage companies from adopting new practices, particularly when cheaper, more familiar alternatives are still available, *"it's competitivity, it's not just like we don't want to be environmentally friendly, it's hardcore business. (A2)"*

Furthermore, the market dynamics play a crucial role in hindering the widespread use of sustainable materials. Many companies have attempted to market green products by promoting their environmental benefits, but these innovations often come with a price premium, which consumers and clients can be unwilling to pay. One expert remarked, *"All these products fail if they are sold for a premium on a large-scale implementation...95% of people will say, 'it's not going to be my money that's going to save the planet.'(C3)"* This highlights a significant challenge: while there is a small niche of consumers willing to pay extra for environmentally friendly materials, the vast majority are not. The construction industry, driven by cost-efficiency and competitive pricing, finds it difficult to justify higher costs for materials that do not provide immediate financial returns, even if they offer long-term sustainability benefits.

The lack of urgency in transitioning to sustainable materials is another factor slowing progress. Traditional materials, such as conventional concrete, continue to meet the basic needs of the industry and are widely available, and "*maybe there was no need to use [sustainable materials] because it worked fine before…They have alternatives. (A1)*" This comfort zone, coupled with the availability of established materials, means there is little incentive for companies to invest in or experiment with greener alternatives until external pressures, such as regulatory changes or resource scarcity, make it unavoidable, *"and this is starting to be seen and felt. (D2)"*.

In summary, while green concrete concepts and biobased materials hold promise for more sustainable construction according to the research contributors, the commercial adoption of such solutions is hampered by the industry's focus on volume, the economic costs of scaling production, resource limitations, market resistance to price premiums, and the ongoing reliance on traditional materials. These obstacles reveal that both economic factors and market dynamics play crucial roles in delaying the widespread use of sustainable materials in the construction industry. The question remains on how these challenges can be addressed, and until then the adoption of more sustainable construction materials will likely remain slow.

6.1.1.4.2 Conceptual and technical challenges from the perspective of material science

In alignment with the barriers that were discussed, the technical challenges that the development and use of sustainable materials face relate primarily to resource availability, heterogeneity, and the techniques of processing such materials. This challenge affects the scalability of these materials, as engineers must constantly adapt to the available resources at the time since now "*we have demolition waste for example from buildings that were built more than 50 or 60 years ago which has a specific composition that will be different from the materials that will come from more recent buildings, and [will require] different treatment processes*".

In terms of design, the complexity of meeting building regulations adds another layer of difficulty. Designers and engineers often face regulations that require adding more materials to achieve standards for comfort, insulation, and acoustics, which complicates the adoption of simpler, more sustainable designs. As one interviewee said, *"We have so many materials, and it's always adding up…I think we need to find out how we can skip layers, but each time we need to add something to make it possible."* Another expert adds that compliance with regulations forces additional material use: *"Do you really need to put that layer…because we have this regulation, this rule that was requested?"* This overcomplication due to regulatory demands can stifle innovation in adopting sustainable alternatives, and drive the choice away from SCMs for example, if conventional OPC concrete is the material that has been studied for the compliance with the regulation in question.

Furthermore, two experts cited performance variability due to variations in chemical composition depending on sources of the SCMs which might affect material consistency and cause compatibility issues because *"SCMs can be challenging and interact differently with other concrete components, like admixtures, and affect workability or durability."*

While the focus is on having materials that are durable – as a circular design principle – one of the issues with new materials such as SCMs of variable composition that have not been studied for long is that only time can tell whether these materials will perform well in the long term or under prolonged adverse conditions.

6.1.1.4.3 Other barriers to the adoption and spread of new material technologies

When it comes to challenges beyond the technical feasibility, the question raised is if it is a more of a systemic issue or a failure of the technology to meet market needs.

The data suggests that the barriers are both systemic and market driven. On the systemic side, the industry's resistance to change is a major hurdle and this reluctance to disrupt established systems prevents the adoption of new materials. One interviewee noted that people simply "*don't like the color changes that new materials can cause in grey concrete, and do not trust new materials that have not been around for long in the market (B3)*" while adding that the general model in people's views is that buildings need to be solid and "*are supposed to last forever*".

Adding on the trust element as barrier to innovation, another expert explained, *"Trust is probably a big problem in innovation, so we need things, and probably in things we cannot see, engaging with technology that we can touch and interact with is relatively easy compared to buildings or new materials."* Which are hidden and abstract concepts that the public does not think about every day despite living and working and using constructed infrastructures constantly. The unfamiliarity of new materials and the lack of visible interaction with them make it harder for stakeholders and especially users to trust and adopt them.

From a market perspective, there is also a clear lack of demand for sustainable materials unless they are economically viable. Sustainable products, when sold at a premium, struggle to compete with conventional materials. As one expert stated, *"Circular economy, the key driver is you've got a better solution for the same price or the same performance for a lower price. That's a winning strategy. If you don't find that spot, I don't care about you, you're not meeting the market needs. (C3)"* In other words, unless new materials can compete on price and performance, the market is unlikely to adopt them widely as fast as needed to accompany the necessary transition of the sector.

Thinking of standards and specifications, some of the interviewees mentioned that the current engineering codes and standards may not fully address the performance of SCM-containing materials *"the engineering codes will have to follow, but always [do so] retroactively (A1)"*, leading to hesitancy among engineers and users alike that might delay the uptake of new solutions in general.

Despite these barriers, some successful cases have been driven by public investments and incentives, which push for sustainable materials in public construction projects. One expert noted, *"I think we've seen some remarkable projects of wood construction...only possible because the public investor had a certain stake and wanted to have this kind of building."* This suggests that incentives that are systemic by nature and public sector support are critical for the wider adoption of sustainable materials be it wood which is conventional or other new material concepts. With the scarcity of resources and the possibility of upcoming restrictions on extractions and landfilling, or carbon emissions for example, the encouragement for alternative solutions at material level to spread and advance becomes more pronounced as noted by one interviewee, *"It's the same with the constructor sector. Once you don't get any materials that there is this stop of supply you just start feeling it and* *you have to do it. Now it's more like philosophical, it's more strategical constrains, but once it gets physical and it will. Then you have to act otherwise. (A1)"*

While project CO2REDRES offers an alternative solution to the cement industry's extraction-emission puzzle it is still confined to the limits of material technology and needs to incorporate elements of circular design to further become a truly circular solution. Albeit an important one, studying materials is only part of the solution and therefore it is important to explore circularity in the wider context that this research proposes for guaranteeing that solutions are holistic and embedded in the corresponding contexts, so that they can assist in contributing to systemic change.

6.1.1.5 Future of the built environment

There are countless reasons to adopt an outlook, particularly when examining fields in constant transformation, as is the case in this thesis. As human societies face an increasingly turbulent and uncertain future, marked by the looming threats of climate change and the complex socio-ecological challenges arising from human-nature interactions, looking ahead becomes essential.

Thinking of the future, might bring already into the mind a picture of how we as humans perceive it, and it prepares us in a way for the challenges if we can think of them ahead. Most importantly, it can connect us with new visions and long-term thinking beyond immediate concerns and narrow interests, and this is what could be taken as an outcome from the interview data analyzed in the last part of the questionnaire, and especially if the outcomes of project CO2REDRES in terms of future needs of research, development and implementation are taken into consideration and juxtaposed to the findings from the interviews.

The different participants had various perspectives on the future of the built environment focusing on shared themes, but also offering distinct visions from one another at the same time. The similarities naturally assembled around a circular and sustainable future with smart and efficient buildings that are integrated with nature somehow and adapted to the constraints that might show up over time. The differences in future visions, however, came connecting to the role of technology and degrees of innovation in design with some economical and practical considerations that varied from one contributor to another. In this section the shared and diverging future visions for the built environment in Luxembourg are explored and commented.

6.1.1.5.1 Shared future visions

The shared future visions among stakeholders are described in this section

6.1.1.5.1.1 Circularity and sustainability

Almost all perspectives expressed concern for sustainability, circular construction methods, and resource efficiency. As discussed in depth in the beginning of the analysis, there's a common vision of moving away from wasteful building practices towards "*having better constructions, better buildings, and more durable buildings*". that are adaptable, and energy-efficient structures, with the reuse of spaces and materials as a recurring theme among interviewees, as well as the mentions of circular design practices such as adaptability of structures and multi-purpose buildings, "*I hope it is a city where we don't have office buildings and buildings for housing, but we have buildings, and they serve the need that we have at that specific time.*" *and "It's really crucial to have … multi-purpose solutions (B1).*", and reduce the need for new infrastructure.

6.1.1.5.1.2 Better designed buildings and construction practices

Part of the mainstream solutions that are heavily discussed nowadays are also reflected in future visions about smarter buildings, not just in terms of technology but also in how space is used and adapted over time. There's an interest in how structures can respond to evolving needs (e.g., no distinct offices or homes or just flexible spaces).

The future of buildings involves better user experience. Comfort and sustainability are emphasized alongside durability and new forms of construction. "*I think buildings in general will become more sustainable, the more people are aware of these things, the more it will develop (A1)*", and "*rethinking places to have several purposes. (B3)*"

6.1.1.5.1.3 Nature integrated and regenerative design

There's a shared sentiment for harmonizing built environments with nature. Some advocate for biophilic design and embracing natural systems (e.g., forests) as part of cities to cool down urban areas, capture carbon, and produce natural materials like wood. Moreover, the concept of nature not seen as something separate but as part of our environment reflects a philosophical shift in how future cities might function in balance with ecosystems, since none of the interviewed experts had radical differences with this concept despite nuances on the degree of connection of regenerative circularity with nature in the future from the practical point of view.

6.1.1.5.1.4 Adaptation and resilience

A common theme is the need to adapt to constraints such as regulations, economic pressures, resource availability, and climate change. Innovation will be driven not only by necessity but also by laws and regulations and external factors that are out of stakeholders' control.

6.1.1.5.2 Diverging future visions

The diverging future visions of the participants are described in this section.

6.1.1.5.2.1 The role of technology

While many agree on smarter and more efficient buildings, there's a difference in how much technology should drive this change. Some advocate for high-tech, smart solutions like better insulation and more innovative materials, while others argue for simpler, more traditional approaches, warning that high-tech solutions may not be sustainable in the long run. The connection that can be drawn to project CO2REDRES here is that the materials used as SCMs are available in nature and do not need great technological input to be used which can be an advantage in future scenarios where digital and energy intensive technology in the construction materials world for one reason or another is not mainstream.

6.1.1.5.2.2 Vision for the urban environment

Some imagine cities with no cars and deconstructed roads, while others focus on taller, smarter buildings due to space constraints (like in Luxembourg). There's a mix of utopian visions (e.g., car-free cities, localized communities) and more pragmatic approaches focused on gradual change. Some voices see architecture as becoming boring with uniform blocks, while others desire a future where creativity flourishes in urban design, and it will all depend on if "*we suffer the future or we build it the way we want*".

6.1.1.5.2.3 Design and innovation

There's a divergence in how fast and radical change should be. Some argue that big innovations are too risky for valuable infrastructure (e.g., buildings worth billions), so small, incremental improvements are more likely, such as better windows or flooring for example. Others believe in drastic changes in how we design and construct buildings, pushing for radical transformation of cities and the built environment as we know it. In this point there is not common ground. When asked about the solutions developed by projects such as CO2REDRES, some considered that it does not fit enough the future of material innovation while other said they think it is a good solution especially that a substitute for concrete has yet to be invented and after a couple thousands of years it still does not exist.

Part IV | Discussion

This page intentionally left blank

7 Discussion

This chapter provides an opportunity to further delve into the results of the research and connect the analysis to the research objectives. It does so by summarizing the main findings of the study in relation to the research questions presented in the introduction and highlights the patterns that emerged and their significance for the research in different parts.

7.1 Connection between materials, stakeholders, and policy

Throughout the research process—navigating structured frameworks, data collection, and analysis—it became evident that the broader system context in which the built environment is embedded serves as the unifying "big picture" for the interdisciplinary approach. This overarching context includes research and innovation activities, industry, experts, and policy and regulation. It thereby integrates and transcends the discipline-specific aspects of the research, blurring the boundaries between individual subsets of engineering and social sciences. Together, they converge and synergize to represent the principles of circularity as a study subject: a circular material technology concept developed in project CO2REDRES, and an analysis of the stakeholder and policy ecosystems on circularity as a continuation in project CO2REDSAP. While the disciplinary boundaries are overcome, new connections and definitions can be established, that before were hard to develop or imagine, as micro ruptures intended to contribute to the dismantling of conventional philosophical and architectural and engineering concepts take place. Afterall, one of the objectives of this research is to generate new knowledge and offer new ways of seeing and connecting elements of circularity in the built environment through material technology and beyond.

From the two projects CO2REDRES and CO2REDSAP, circularity as a common denominator emerges into the spotlight and provides a picture on the local ecosystem of the circular construction economy in Luxembourg from three angles: materials, policy, and stakeholders. In broadlines, the connections mapped from the patterns seen in the data are as follows:

(a) materials and policy

Throughout the interview analyses, there was a general convergence that policies driving material choices where guidelines and mandates on material use or limitations or even recommendations that promote sustainable alternatives is a positive step that makes the adoption of sustainable alternatives, and the research and development efforts advance quicker than they otherwise would.

However, there is also the possibility of material innovation influencing policy, but rather at later stages beyond the experimental adoption, and only after industrial stakeholders have invested in process changes that then require a push for regulation and incentives (financial or not), and this is often intersectional with other objectives that need to be reached and that are related to either the scarcity or decrease in supply of conventional raw materials or the side-effect of other advanced regulations such as carbon emission reduction for example that prompts a change in material mix and composition.

In short, the policy-material connection can essentially work in two ways: (1) policy as a catalyst that is the starting point for change, or (2) the necessity of adoption of new material technologies due to external forces e.g. production shortages, or changes in other policies that affect material supply and demand, etc. pushing policy changes to allow for new uses.

For the time being, the main relationship between materials and policy is centered around emissions aspects and climate targets rather than circularity concepts, which could still benefit from several improvements. As presented in the interview results, a shift from individual material focus to systemic approaches is part of the needed transformation since current strategies often target individual building owners or specific structures. Broader measures that address systemic material efficiency—such as the promotion of circular construction practices—require greater emphasis. This includes policies that encourage together the use of materials in a circular manner and the reduction of embodied carbon across the value chain, which highly relates to the research purpose of project CO2REDRES in first place.

Overall, while there are promising ideas around sustainable building materials, the public policy strategies remain focused on energy efficiency and carbon emissions and does not address material aspects in depth, and although some elements are systemic, they are not reflected in concrete timelines or implementation plans in the building sector.

(b) materials and stakeholders

This connection is more related to the interactions and decision-making processes that underline the relations between stakeholders that have been previously mapped (see section 6.1.1.2). Various factors are taken into consideration when stakeholders choose certain material technologies over others principally when trying to balance cost, performance, availability, and environmental impact. While stakeholders influence material adoption, the reverse is also true because sometimes material choices influence stakeholders, especially the ones that are not decision-makers in this link such as nature represented by its fauna and flora, operational workers and communities of a built environment.

In the end it is an overlap of financial and non-financial decisions that influence material choice, and this is one of the ideas that diverged in the interview data with some contributors giving a higher weight in decision making to the economic-financial impact and others who saw that if anything needs to change it is the way stakeholders think and the awareness around the need for a deeper level of transformation in the built environment. In project CO2REDRES, the stakeholder element was of utmost importance and played a significant role in the project's evolution as partners from the Greater Region came together to supply and study different materials, and this represents some of the interactions that were mapped in project CO2REDSAP which overlap with the ones experienced in the former. Therefore, it is safe to say that stakeholder collaboration is one of the ways forward in transforming the built environment, and it needs to continue beyond specific projects and expand its topics of discussion to account for the influence of interdisciplinarity and the real-life pragmatic solutions to complex problems.

(c) policy and stakeholders

Unlike the previous connection which was present in project CO2REDRES and its discussions the policy-stakeholder dimension was barely discussed. On the other hand, in project CO2REDSAP the topic of stakeholder engagement in policy development was always present, with experts across the three different sectors the public, private and academic affirming that effective policies often emerge from consultation with different stakeholders, given that the technocratic sphere of government is in constant touch with the industry. Moreover, Luxembourg seems to integrate well cross-sectoral connections at least in the public administration where all interviewees perceived some level of inter-sectorial collaboration on projects and strategies and gave practical examples of working together with other departments. However, to some of the participants other important stakeholders such as the community and users are not always fully included in the bigger picture, especially when the strategy in question is not a national wide plan such as the PNEC and PNGDR, and when included their input is secondary. Despite the importance attributed to the participatory process of different stakeholders in the interview data collected, on the spectrum of including regular citizens in the decision-making process as part of policy development, some contributors were in favor, other neutral, and a few opposing. This gives a window into how different ontologies affect this connection by either considering that the built environment is a technical space in which the best form of decision-making is dominated by expert input in contrast to another that sees it as a plural space in which all the involved stakeholders should have a voice even if they lack a certain level of technical understanding of structures or materials. Whilst quality criteria for building materials relating to load-bearing capacity and chemical composition for example may be an expert matter, environmental impacts of their production and circularity are quality criteria that relate to our common future in a way that is relevant to all stakeholders in a building, including users, developers, neighbors, etc. The involvement of non-expert stakeholders ensures that the solutions are truly fit for the communities they aim to serve, and that "*technological innovations [are] at the service of the users. (D2)*", through the co-production of knowledge and the democratization of expertise as argued by *Jasanoff* in Technologies of Humility [341] relating to science, and the EU Commission's white paper on governance [342] relating to policy.

As a conclusion to this connection, it is a common perception in interview data that engaged stakeholders are able to ensure relevance and feasibility of policy on circularity in general and materials in specific, and they hold a responsibility in implementation and adherence to the components of the different policy elements which in turn enhances the ambition of material regulation, part of what is missing with regards to project CO2REDRES findings that suggest that it is feasible to have circular practices in materials at research and development levels, yet this is not translated into the real market. To sum up the interactions in the policy-stakeholder connections beyond materials into sustainable development, Figure 81 brings the intersections of policy influence and stakeholder involvement as can be summarized from the interview data analyses chapter.

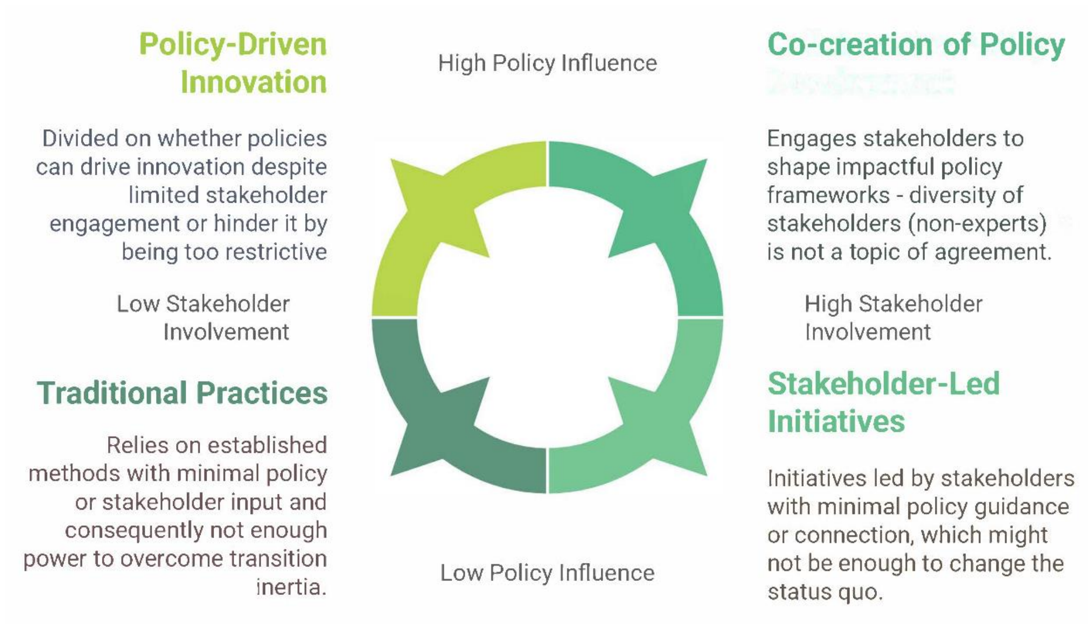


Figure 81. Intersection of policy and stakeholder involvement.

Through analyzing the different quadrants and connecting back to project CO2REDRES as an example of an action situated at the bottom part of the figure between the third and fourth quadrant where elements of innovation are embedded in a scenario of low policy influence and middle stakeholder involvement, therefore not able to create substantial change with its outcomes.

(d) Integration of all three subsets

Addressing complex challenges such as circularity in the built environment and the use of unconventional SCMs on a larger scale requires linking material innovation and technology to supportive policy frameworks and stakeholder cooperation as has been demonstrated in the data analyses of the interview outcomes. To achieve a goal of a regenerative sustainable built environment, the transformation needs to happen on all axes together and with all stakeholders collaborating to create viable solutions that go beyond the disciplinary silos.

Therein lies the complementarity of projects CO2RDRES and CO2REDSAP to show the interdependency of the various disciplines that are still separated in practice. Without having studied the material aspect and concluded that there are feasible alternatives to conventional OPC concrete that are not mainstreamed into the industry, the need to study stakeholders and policy would not have been so important, as one would always consider that the technical aspect is sufficient to mainstream a solution, especially in the engineering field.

The connections between materials, stakeholders, and policy, as outlined in the three previous sections, reveal that achieving circularity in the built environment requires an integrated approach that addresses all three dimensions simultaneously. The materials-policy link shows that while policies can catalyze material innovation through guidelines, incentives, and regulations, innovation can also push policy change at various stages and levels. The materials-stakeholder link demonstrates that the adoption of sustainable materials depends on a mix of financial, performance, and environmental considerations, with collaborative networks such as those formed during CO2REDRES playing a key role in advancing material technologies. Finally, the policy-stakeholder link highlights that policies are most effective when stakeholders are fully engaged in their development, ensuring both feasibility and implementation, yet gaps remain in involving non-expert communities in decision-making processes most of the time.

When these three dimensions are considered together, it becomes evident that systemic change requires co-evolution across all axes: material innovations should be embedded within supportive regulatory frameworks, and these frameworks should be shaped and implemented by actively engaged stakeholders at all levels. This integrated perspective builds on the complementary findings of projects CO2REDRES and CO2REDSAP, demonstrating that technological feasibility alone is insufficient for mainstreaming circular solutions in the built environment. Only when material technologies, policy instruments, and stakeholder networks work in synergy can scalable, regenerative practices emerge. This approach moves beyond disciplinary contexts, fostering interdisciplinary collaboration as a possibility and alternative to move on from conventional linear disconnected models and enable truly circular construction economies.

Therefore, the connection between the three subsets of this research, namely material technology, stakeholders, and policy is established and justified by the added value that the connections between each of them individually and all the three together offer to this research project and the real-life adoption of regenerative circular solutions for the future of the built environment.

7.2 *Patterns emerging from the results:* commonalities and contradictions.

Through the interdisciplinary analysis, several emerging patterns were identified, shedding light on the interconnected challenges and opportunities in advancing circularity within the built environment. These patterns reflect the complex interplay between material flows, policy frameworks, stakeholder collaboration, and technological innovations in materials (e.g. project CO2REDRES) and elsewhere, highlighting both recurring themes and unique insights across the disciplines involved.

7.2.1 Overarching themes of consent

Three main patterns of consent from interview data analysis can be summarized in this section.

7.2.1.1 Transition urgency

Independently of the circularity definitions that were explored in section 6.1.1.1 and the different views on the subject, the urgency of transitioning to sustainable practices has been a common denominator and the notion that delayed action risks compounding the challenges, making recovery more costly and complex where the quality and cost of solutions have to accompany the ever more complex nature of the problems that are left unsolved. Although the object of this research is not the discourse analysis, it can be inferred from the interview data that there exists a general agreement on the fact that something needs to change in a fast manner, and that the direction of this change needs to lead to a more sustainable built environment on the long run. However, apart from the urgency, the degree of disruptiveness of this change to established systems and norms is not a term upon which the experts agree.

Humans have witnessed the transformation of concepts and ideas once regarded as unquestionable, spanning social constructs, cultural values, and advancements in science and technology. Just as revolutionary developments in physics shifted our worldview from a mechanistic Newtonian perspective to a holistic, ecological understanding, embracing new paradigms is rarely straightforward, as Capra puts it [339]. Scientists of the past had to evolve their thinking and frameworks to describe new phenomena, and today, we face a similar imperative. As we deepen our understanding of sustainability challenges, we should recognize that change is a constant. The more we learn, the more we need to adapt, acknowledging and embracing this continual evolution. Therefore, having a perception of urgency is positive in a way that it prepares the ground in the context of the built environment to accept change and to work on the assumptions and underlying beliefs - i.e. the importance of ontologies discussed in the results section – that stakeholders hold.

7.2.1.2 Circularity as a positive development

Complementing the idea of a needed urgent transition, seeing circularity as one of the solutions to the sustainability conundrum is already a fact that helps with setting goals and interventions that can lead to the desired change. The fact that the result analyses from both projects CO2REDRES and CO2REDSAP allow for a conclusion that circular ways are indeed good transition strategies for the construction industry not only to reduce its carbon emissions and achieve neutrality, but also to shift prevailing models to value regenerative and net positive circularity, makes it clear that the impact that circular solutions have are in general positive on the sustainability aspect of the construction when considered holistically. To match the literature on circularity back to the results of the interviews, the rule of thumb is that a higher level of circularity implies fewer natural resources exploited and less environmental pressure [212].

7.2.1.3 Hurdles to transition remain strong: stakeholder engagement and the cost of circularity

The third point of agreement is in part a product of the first two. If transformation or transition is urgent and viewed as having a positive effect, then the obstacles it faces are substantial, otherwise it would have naturally happened. The possibility of change exists, however there are many hurdles, several of which were mapped and explained under *Challenges and barriers to circularity in Luxembourg* in section 6.1.1.1. As seen from the analysis, different challenges exist at different levels on a spectrum - some deeper and more complicated than others while others simpler in comparison. The solutions proposed (see Figure 79) are then related to joint action and the power of stakeholders in working together for change and using policy as a lever for circular economy transitions as expected from the focus topics of the interview questions and the outcomes from the stakeholder relational mapping. Nonetheless, the cost of circularity still remains one of the challenges that were widely mentioned in the interviews and need to be addressed so that a system of integrated solutions such as the one proposed is able to be deployed. In the current prevailing business and economic models in the construction sector, cost is an important variable according to the experts. Therefore, solutions need to be creative and align with new visions of design to overcome such challenges, and circularity is a design concept in essence as the literature chapter revealed.

In this context, the work of Manzini in his book *Design*, *When Everybody Designs* [343], for example, shows a transition design framework that brings at its core an approach to addressing complex societal challenges by fostering systemic change towards sustainable futures. Applied to circular economy, this framework encourages a shift from focused problem-solving to designing for long-term systemic transformation in which reimagining futures is essential to bridge the gap between immediate needs and sustainable built environments in the research context.

To overcome challenges through design, the framework suggests visions of communities that co-exist in symbiotic relationships in the ecosystems in which they are present, where transition is informed by new knowledge about natural, social, and built or designed systems that will in turn reshape mindsets and postures of designers through new theories of change. Manzini's approach is based on participation and collaboration and systems thinking in local contexts which is highly aligned with the research framework of the qualitative part of this thesis that addresses stakeholder interaction in Luxembourg and acknowledges the importance of their collaboration to co-create solutions that work and happens to be an overarching agreement point between interview participants. While the hurdles remain strong, change theories that inform and define pathways for systemic change become important elements in the transition web that the sustainable built environment belongs to in the present. In discussing solutions through design, other works related to circular economy align with the outcomes of this research ranging from the ideas on the practicalities of circular design with W. McDonough and M. Braungart [163] in *Cradle to Cradle: Remaking the Way We Make Things* and W. Stahel [344] in *The Performance Economy*, who respectively introduce the concept of designing for cycles where materials are either biodegradable or endlessly reusable and emphasize product-life extension and circular business models through the cradle-to-cradle concept, all the way to broader views on design with the examples of the transformative regenerative development concepts, as well as authors who integrate design thinking into creating sustainable systems that align with circular economy principles. In each of the two projects CO2REDRES and CO2REDSAP, elements of circularity are evidently present, either at the concentrated and focused material level or at the system level with stakeholders and policy at the core, and this is one of the important parts of this research because by combining these ideas of consent the findings of both research parts – the quantitative and qualitative – represent opportunities for moving forward and aligning the construction industry shift towards sustainability and resilience through recognizing the challenges and laying down the solutions. Project CO2REDRES is an example of how far forward stakeholder interaction can push the materials industry in the construction sector when common objectives are defined, and how the cost of transition still needs to be handled differently, to be able to mainstream solutions that require more than capital investment and might not bring in commensurate profits as the regular ones.

7.2.2 Contradictions and divergences

The expert perspectives encountered during the interview discussions on how to achieve circularity in the construction sector often diverge, reflecting a complex interplay of technical, economic, regulatory, and social considerations shaped by the different worldviews of each participant. This discussion chapter previously explored aligning viewpoints and in this section delves into the differing viewpoints, highlighting three key areas of contention among the professional interviewed. By examining these divergences, the discussion aims to uncover underlying barriers to circular practices in construction, offering insights into how diverse perspectives can inform better strategies for a sustainable transition.

7.2.2.1 The means of circularity

As very recent studies published in 2024 such as the Building Prosperity [330] by the Ellen McArthur Foundation start to touch upon the value of a circular economy in the built environment that is regenerative by design and symbiotic with nature, in line with earlier studies and publications from authors such as Cole, Reed, and Plessis [237], [251], [252] to cite a few, the systemic change concept starts to gain traction. Meanwhile, the connection between a holistic, regenerative and nature-positive model circularity and its counterpart a technocentric model circularity starts to show its signs with local projects becoming more circular in design at different level beyond material technology and energy efficiency.

However, the divide among experts can still be seen in the interview data analysis and many can't seem to agree on how to reach holistic circularity, and more so, if it is even possible. From the point of view of project CO2REDRES, for example, a 100% substitution of OPC is more than a technical challenge because it represents rethinking the whole industry, even the recycling part that makes concrete greener and less CO_2 intensive, but other available ways of carbon reduction, storage, and sequestration are present and used, thus limiting the scope of solutions to the technical sphere in this case.

Throughout the interview analysis the two models of circularity were present, and often elements from one and the other permeated the content within the same interview with the particularity that the more technocentric approaches were related more to a question of economic priority (e.g. profitability, competitiveness, and green growth) and efficiency drive (resource productivity, cost reduction, and technological advancements) than having narrow scopes that focus on processes such as recycling or limited integration of social elements and systemic issues. Although not unanimous, the holistic circularity line of thought presented some window on focusing on transformation considering behavioral change of stakeholders and governance as important means for circularity, and the emphasis on circular design that gives way to systems that align with social-ecological principles. Therefore, the difference in the two models is the dimensions they prioritize with their focus and approach to design.

To relate this to the material part with the quantitative analyses in project CO2REDRES, is to also reflect on the priorities of the sector in general and ask the question whether looking at material circularity in the way it is done is enough through technical feasibility, and environmental impact analyses. As project CO2REDRES went beyond the material technology assessment with partner universities (University of Liege) studying the environmental impact of using different SCM substitutions from the project through LCA methodology, it was a step forward towards including other metrics than technical feasibility and pozzolanicity potential into decision making, but it stops at environmental benefit, falling short of studying the systemic reasons as to why sustainable material concepts are not mainstreamed in the industry.

7.2.2.2 The goal of circularity

Following the discussion on the means of circularity, i.e. the dichotomy represented between regenerative nature-positive and a technocentric way of consideration, the goals of circularity, its purpose, and who does it serve. The participants' views spanned a spectrum, from seeing circularity as a way to create economic value by minimizing waste to benefit businesses and people in a world of limited resources, to viewing it as a goal of environmental sustainability aimed at fostering a regenerative planetary future. Additionally, some participants emphasized addressing social aspects alongside these goals. Interestingly, their perspectives often varied depending on the specific part of the built environment and construction industry they were discussing. Therefore, the goals of circularity are not common among all stakeholders, and those are aspect-dependent.

This makes the relationships and exchange between stakeholders ever more important to create a transition that is technically sound and practically regenerative, which highlights the significance of looking at such connections in the stakeholder map created, fostering them, and creating new ones where none are visible, since the evolution of circular economy is a collaborative effort that is always under construction.

7.2.2.3 Distributional issues of circularity

The implementation of circular economy strategies impacts stakeholders in unequal manners, which generates diverse threats but also opportunities. The interviewed experts saw different degrees of how the transition impacts different stakeholders and how it might deepen existing inequalities or create new ones. On the one side, some experts believe that circularity policy should take into consideration these effects and through engagement and financial assistance mitigate threats, while others estimate that smaller market players might not be able to navigate major changes to their processes no matter how much the transition process is inclusive, and usually it will be at the cost of their survival.

Even though this was not a point raised by everyone, it relates directly to the framework of project CO2RDRES in which major stakeholders are mining companies and cement manufacturers. There, the distributional issues might arise from resource extraction and processing where circularity aims to reduce extractive practices therefore industries such as mines and quarries for example might experience economic decline, on top of that, regions that have already advanced infrastructure to support circularity with material recovery technologies will lead the way while other regions might not be able to perform equally. On a similar level, technological and knowledge gaps such as access to innovation and capacity building might not be easy for smaller and budget-tight enterprises.

Despite the different views on the exposed matter, and the belief of some experts that financial intervention is enough to solve distributional issues, others considered that there is more to it and that on top of inclusive circular policies that explicitly consider the needs of all parts including nature, stakeholder engagement in circular economy planning and decision-making is also important to reverse such potential issues. In a way the concept of extended peer community from post normal science, suggests the traditional boundaries of the scientific community are extended to include all stakeholders, recognizing that non-experts can contribute valuable knowledge and perspectives [31], which is a concept that drew a border to certain participants on non-expert interaction, while others welcomed openly.

7.3 Reflections on circularity

In qualitative research, participants' beliefs, values, and experiences play a central role in shaping the data, as they offer insights through their unique perspectives, and therein lies the richness of the data in terms of diversity. The collection of these individual elements influences the worldviews held by individuals and consequently by groups. According to *Cole* [253], these worldviews that shape our understanding of the world around us evolved over centuries to influence human activities including building practices, and since the 17th century, the prevailing worldview in the construction industry and the built environment in Western societies has been largely shaped by Cartesian-Newtonian and mechanistic thinking. This perspective views human enterprise as dominant over and separate from nature, driving construction practices that exploit natural resources, focus on short-term benefits, and develop infrastructure with little consideration for environmental impact.

Starting from that idea and delving into the overarching themes that were revealed in the interviews drawn from the previous parts of this discussion, it is true that regardless of the difference in worldviews, the participants converged around the need for some kind of change and a quick transition into a more sustainable built environment, indicating that it becomes ever more persistent that this transition in the construction industry is part of the future they envision. However, the more holistic their vision of circularity, the more equal importance they attributed to all aspects of the built environment rather than a focus on a technocentric approach aligned with R-strategies and economic considerations.

To understand better the intricacies of the research finding's relation with worldviews that shape people's visions, the last coding segment of interview data named "*reflections*" was chosen to describe certain parts of the analyzed interview data that were not necessarily related to the initial structure conceived to answer the research questions on circularity, stakeholders, and policy, but one way or another are too rich to leave out of the discussion in this section. These reflections underscore the need for a mindset[4] shift *(B1, D1)*, interdisciplinary collaboration *(A1)*, and a purpose-driven approach *(C3, A2)* to truly embrace regenerative holistic circular practices in the construction sector. The emphasis on collective intelligence, regulatory evolution, and post-ecological (beyond ecological considerations) inspiration paints a picture of a field on the edge of transformation but still grappling with deeply entrenched norms and challenges that if left entangled might hinder a transition towards a truly sustainable future in a full sense.

Taking decisions based on the most appropriate course of action—whether it be to preserve, reuse, or repurpose—depending on specific criteria. This holistic mindset acknowledges the complexity of circularity and the diverse factors that must be balanced in decision-making processes. *"And we as actors of this circular economy change, we need to put purpose first, and then use the tools. (C3)"*

Circular practices represent a paradigm shift in how we approach construction, design, and resource management. Central to this discourse is the recognition of *"collective intelligence as a critical driver of change (D2)"*. Professionals and designers are called upon to move beyond individualistic methodologies and embrace collaborative problem-solving. Circularity thrives when diverse stakeholders unite to work cohesively towards common goals, pooling knowledge, expertise, and resources.

An often-overlooked aspect of circularity is the post-occupancy phase of buildings and spaces, "*we are so trained to overconcentrate on the technical parts that it influences how*

[4] The definition in this context is not related to any of the scientific theories on mindset, it rather refers to the set of attitudes, beliefs, and assumptions that shape how a person interprets and responds to situations. It is the mental framework through which individuals perceive the world, make decisions, and approach challenges.

we see the world around us and consequently the built environment (B2)". While metrics such as energy consumption and emissions are routinely evaluated, the broader social and environmental impacts remain inadequately addressed. This gap highlights the pressing need for more interdisciplinary approaches that integrate social sciences, engineering, and design to holistically understand and address these impacts.

Resistance to change within the construction industry also poses a significant challenge. Many professionals, shaped by traditional training and accustomed to established practices, are reluctant to adopt innovative approaches, "*following the rules does not allow for smart decisions (C3)*". However, history suggests that once new regulations are implemented and their benefits become evident, the industry adapts. This underscores the importance of balancing innovation with regulatory frameworks that guide and accelerate the adoption of circular practices.

The current emphasis on simplicity, certainty, and immediate results often leads to designs and methods that overlook the long-term sustainability and resilience of the built environment. "*To truly embrace circularity, we must [shift this focus and] prioritize enduring value over short-term gains*". In addition to value, a critical reevaluation of the purpose of construction with buildings and urban spaces designed to address societal needs efficiently, rather than perpetuating individualistic tendencies was also a reflection on the reality of the built environment.

The interview conversations raised a profound question too on whether *"we want to design our future proactively, or merely react to changes as they arise? (C3)"* A proactive mindset is essential for addressing circularity holistically. This requires clear priorities, criteria, and ambitions to be established from the outset, ensuring that design and construction align with long-term sustainability goals that are set by society.

Nature, particularly forests, serves as a powerful metaphor and model for circular practices. Forests are efficient, self-sustaining systems that exemplify how resources can be cycled and reused seamlessly. *"If we look at how forests work and get inspired again … we as humans knew how to cooperate with nature in our history (D2)."* By reconnecting with natural processes, we can probably find inspiration for smarter, more resilient construction practices that align with ecological principles.

Ultimately, the conversation recognizes the intricate, multifaceted nature of circularity in the construction sector. There is no one-size-fits-all solution; rigid frameworks are insufficient to address the unique challenges of each project. Adaptability, openness to diverse perspectives, and continuous learning are key.

Linking the reflections on circularity in the broader context of the built environment to the material part, and project CO2REDRES, it is possible to draw connections to the question of SCMs being stocks of waste material that are already out of the loop of the respective industrial processes. Most of the research in CE focuses on flows but not stocks [171] and in the built environment it is as important to focus on both. The future waste is already there, so a real circular economy approach is one that takes into consideration how to deal with massive stocks and involved secondary materials as well [164]. Another connection is that of using resources in a full manner with the least extractive practices following the metaphor of forests and looking for the utmost value in materials that are generated in production cycles, as well as changing mindsets to view waste as a resource and thus eliminate the concept of waste wherever possible. And here lies in a connection to policy as well that started doing this with nomenclatures and waste hierarchy concept in the latest national law, but still has a way to go.

7.4 Implications of findings for research and practice

As the research draws towards the conclusion, it is important to revisit and discuss the implications of the findings in the scientific process and how do those contribute to knowledge in the fields. Since this study adopts an interdisciplinary lens, merging insights from material science, policy studies, and stakeholder analysis to address these complex challenges it was able to uncover synergies that can accelerate the transition to a circular economy in construction and outline the current state of circularity in the built environment in Luxembourg. In doing so, it underscores the need for integrated approaches that combine technical advancements with systemic change, paving the way for a regenerative sustainable transition.

7.4.1 Material science and engineering perspective

Studying the properties of various SCMs from the Greater Region, and their pozzolanic potential, contributed to advancing sustainable construction material technologies since the research project CO2REDRES could identify SCMs with pozzolanic properties, promoting the use of sustainable alternatives to conventional OPC. Despite the fact that it is not a 100% substitution alternative that would see the end of using Portland cement in concrete (the study was carried at up to 20% wt), it is a step forward towards identifying new materials and setting out the direction of the search for SCM and their desired properties, which can inform future industrial practices in both the cement industry and the mining and quarry processes, etc.

On top of reducing the carbon footprint of construction materials and encouraging resource efficiency, the addition of SCM can enhance material circularity by eliminating waste in the gravel quarries in first place, ushering their business models and processes into circular approaches already. The insights created into material circularity could lead to innovations in recycling and repurposing by-products such as waste clays and GWM, closing material loops and minimizing waste. The quantitative findings on pozzolanicity and the suggestion of the set of tests to classify materials might contribute to improved life cycles that can see processes of extraction and landfilling valuable materials change.

7.4.2 Policy and stakeholders perspective

Starting by the collaboration of stakeholders from project COREDRES that counted with 4 academic research institutions and 13 industrial partners, and expanding into the findings of CO2REDSAP, the results from the stakeholder mapping could help identify key actors and their roles in implementing circular practices, fostering stronger collaboration across industries, government, and academia. Moreover, by studying the drawn connections, one can understand better stakeholder concerns and priorities which in its turn may help in addressing resistance to change, accelerating the adoption of regenerative circular practices and materials.

In connecting stakeholders to policy, the research highlighted disparities in stakeholder capacities (e.g., SMEs vs. larger companies vs. users) and in diffusing the results, this can be a catalyst to propose that more equitable approaches that ensure inclusivity in circular transitions are reflected in policy implementation.

While policy in context and connected to stakeholders and their decisions and worldviews is important, as a standalone topic it is also concerned in the implications of this research. By studying its connection to different ontologies, the research reveals how policy elements accommodate the development of circular frameworks and push for a holistic vision of circularity or not. From discussing holistic metrics to assess circularity to providing pragmatic action in policy that leads to a regenerative circular transition towards sustainability, it all opens up a new way of looking at policy through another lens: the ontological one.

7.4.3 Interdisciplinarity perspective

This thesis bridges diverse parts in engineering and social science and by integrating these fields, it creates an example for tackling complex sustainability challenges through interdisciplinary approaches in research. This framework not only enhances the understanding of circularity in construction but also demonstrates how diverse expertise can synergize and complement each other. While researching material science and thinking of the role stakeholders play in adopting circular solutions, the research cross pollinates social science and engineering.

The methodology and findings from this research could also inspire the development of more interdisciplinary research projects that address the interconnected nature of sustainability and provide novel ways of navigating the complexities of sustainable development. By addressing both technical aspects—such as the pozzolanic properties of SCMs in project CO2REDRES —and systemic challenges like stakeholder dynamics and policy frameworks in project CO2REDSAP, the study paves the way for future interdisciplinary research. It highlights the importance of holistic approaches to circular design, fostering connection across disciplines and with the real world, and showing that research undertakings can explore new pathways for sustainable development.

7.5 Relation of the findings to the conceptual framework

The conceptual framework of this research (discussed in Chapter 5 and Figure 76) that outlines the roadmap with the topics followed during the interview questionnaire and the data analysis, evidently goes beyond the material technology aspect studied in the first part having in common the circularity aspect. From CO2REDRES to CO2REDSAP, the research takes a zoom-out from the mineralogical-chemical level to the macro social-ecological level. At the core of this framework are different understandings of circularity according to three ontologies, specifically: the positivist, the social-constructivist, and the pragmatist. By borrowing the concept of these three natures of reality and applying them to the context of circularity in the built environment, the research connects the studied policy elements, stakeholder relationships, and the regard of participants towards circularity to the intricacy of the built environment as a complex social ecological system. The system in question requires holistic approaches to problem solving that the current reductionist approaches cannot address, and in which the transition process towards a regenerative form of sustainability - that offers net-positive benefits (gives back more than it takes) - is shaped and informed by all stakeholders [249]. Therein lies the importance of having coherent policies and stakeholders who interact in ways that are compatible with the pathways needed for the futures that they want to build.

7.6 Possible limitations of current research

The complexity of combining multiple domains and the practical challenges inherent in addressing both specific and broad sustainability issues in interdisciplinary research on circularity come with some limitations.

Data availability and quality is one of the first potential issues to reflect on. In project CO2REDRES, taking samples from material deposits that are and have been formed over the years by different processes, circumstances, and industrial practices can lead to having other layers of material with a varying composition and therefore raise questions on homogeneity and stock quantification, which is a legitimate point especially prior to engaging in industrial scaling of solutions. Translating to qualitative research, with a locus around data, it is always a possibility that certain interviewees might have withheld information due to confidentiality reasons, or other concerns, which may influence the research outcomes.

Apart from data, practical implementation can be a discussion topic due to scalability limitations since the findings from lab-scale studies on the studied SCMs may not translate directly to industrial applications due to differences in scale, equipment, or environmental conditions. However, this should not constitute a block as one of the industrial partners of project CO2REDRES was already investing in new infrastructure for clay calcination that can be a proper solution to the valorization of the studied SCMs in this research. Similarly, in the qualitative part, policy recommendations may face challenges in adoption due to existing regulatory frameworks, resistance to change, or lack of political will, and stakeholder engagement as an outcome of the mapping exercise can also be challenging in engaging all relevant actors effectively and aligning their interests, especially in situation where there is competition or non-symbiotic interaction that can reveal threats and weaknesses of one of the parties.

In terms of timeline, the research is part of a PhD study which has a start and end date and cannot easily assess long-term impacts in this frame. As it is just starting (if compared to other material uses), the benefits of circularity and the adoption of SCMs may take years or decades to fully achieve a significant scale, making it difficult to measure long-term impacts within the timeframe of a single research study. This, together with changing market and political conditions, technological advancements, and evolving stakeholder priorities may alter the relevance of findings over time, especially in the qualitative section.

These limitations highlight the need for a cautious and transparent interpretation of findings that relies on a sound methodology and analysis, all while highlighting the importance of iterative research, collaboration across disciplines, and suitable approaches to address emerging challenges and practical implementations.

8 Conclusion

8.1 Summary of key findings and their significance

Reaching back to the research questions first set out in Chapter 1, section 1.4, the first set of was addressed mostly through quantitative laboratory analyses as described throughout Chapter 3. Various quarry and industrial by-products from the Greater Region were collected and characterized for their chemical composition, mineralogical phases, and physical properties using standardized tests. Their pozzolanic activity was assessed through reactivity indices, strength activity index testing, and performance evaluation in paste and mortar specimens. The results then presented in Chapter 4 enabled correlations between pozzolanic properties and mechanical performance, while also providing data for decision-making frameworks and scalability considerations.

In the second and complementary part of this thesis a second set of questions was answered, but this time using qualitative data from semi-structured interviews with experts and stakeholders across the built environment sector in Luxembourg as described in detail in Chapter 5. The interview data was analyzed thematically to map stakeholder networks, explore perceptions of circularity, identify policy influences, and highlight systemic barriers. This analysis also revealed how policy-stakeholder interactions shape the uptake of new material technologies (related to CO2REDRES) and informed the development of systemic solutions to overcome the challenges faced by circular practices in the construction sector in Chapter 6.

While project CO2REDRES brought the novelty of studying the pozzolanic activity and the potential of using SCM originating from the Greater Region that were not studied before, it built on the findings of previous research [24], [25], [27], in creating a continuity to findings that culminated in confirming that there is a possibility of using such SCM after studying their properties.

On the technical side, the chemical composition showed that the majority of samples are rich in silica and alumina (at least 70% mass - to a slightly varying degree), and mineralogically rich in quartz-illite or quartz-kaolinite content, which is essential for their performance as discussed in the literature on reactivity. The research also found out that the particle size distribution of the studied SCM is comparable to those stipulated in international norms for other industrial pozzolans [105], and not less importantly having a strength activity index greater than 75% of the reference sample in all 750°C specimens at 28 days. All this together with the direct pozzolanicity tests show that such materials that are abundant in the quarry industry as secondary or waste materials can be reintroduced into the cycle for a more circular approach to the extractive practices of gravel mining.

The findings gave a tool for industrial partners to be able to assess the potential of the so-called waste that is generated from their original processes, and insights on what constitutes good quality SCM in this case, that might inspire them to do things differently by adapting their processes to valorize their deposits, reduce landfilling, and get one step nearer to close the lifecycles of their products.

These findings were equally important to inform the second part of the research on stakeholders and policy and as to why circular solutions in the construction industry are not yet fully implemented or industrially scaled knowing that solutions such as the ones proposed in project CO2REDRES are already part of the present.

Project CO2REDSAP offered a window on how certain connections between stakeholders can help advance the implementation of circularity in the built environment beyond just the stakeholders involved in the material part and mapped certain symbiotic or conflicting connections that can be developed further or adapted for a desired outcome respectively.

As a continuation, the findings revealed further information on the circularity policy landscape in Luxembourg, primarily an absence of a specific all-encompassing sustainability or circularity policy for the construction industry, where the latter relies on elements of circular policy from other documents, strategies, roadmaps and laws to incorporate sustainability aspects. On a more specific quest relating to project CO2REDRES, there were certain connections established from the policy analysis that relate to the circularity aspect in materials, but nothing was found that directly connected to the SCM part, especially the types of materials studied in this thesis project. Therefore, a conclusion can be made about the influence of policy in the uptake of such material technologies that rely solely on the interest of a handful of stakeholders in valorizing such materials.

Regarding prevalent ontologies in policy, the data analysis showed that while there are some elements of a pragmatist approach in some of the studied policies cited by the interviewees, there is mostly a presence of isolated actions that stop short of taking into consideration the systemic nature of a regenerative circularity transition model. Therefore, policy has an opportunity to promote actions beyond recycling and reuse.

As a connection to effective policy, participants also allowed a general conclusion on the lack of proper measurements of circularity and evaluation of sustainability policies and practices alike, which circles back to the introduction chapter and echoes other studies of the same topic focused on other European countries, for example *Giorgi et al*. [6] among others.

8.2 Contributions to the field CO2REDRES

Project CO2REDRES, on top of bringing together important stakeholders in the field, investigated materials that can potentially present three advantages at once by using GWMs as SCM: (i) the reduction of extraction of natural resources with less need for limestone mining, a main component of cement, by decreasing OPC content in the binder matrix, (ii) the valorization of industrial waste materials implying a reduction in landfilling and waste management issues for industries and the state and contributing to circularity in the construction industry, (iii) reducing the total energy intensity by decreasing the clinker to cement ratio since the GWMs are calcined at lower temperatures than the decarbonation process takes place at during clinker manufacturing. The pioneering aspect of this study is evaluating the potential of various waste materials from the Greater Region that have not been studied before and suggesting ways of valorizing them to the industrial partners of the project and therefore creating a step towards closing the material loop through using waste deposits.

8.2.1 Advancing material science concepts

By identifying new SCMs and characterizing novel materials with desirable pozzolanic properties, offering alternatives to traditional options in decline like fly ash or slag, the research helps expand the use of clay-based materials beyond metakaolin and pure clays which are often associated to extractive processes rather than by-production or waste.

Understanding the pozzolanic behavior of these materials allows for the optimization of concrete performance, including strength as the research results showed in chapter 4. Insights into the reactivity and compatibility of novel SCMs, such as the ones studied, can lead to the development of innovative mix designs tailored to specific applications or environmental conditions, especially when long-term properties are studied in the future. The material circularity element lies in the elimination or reduction of waste from the quarry industries by valorizing the studied SCMs but could expand to the construction phase with circular design beyond the material aspect.

8.2.2 Supporting regional industry transition

Researching materials from industrial partners that have been mostly in landfills, or deposits for the last years facing certain difficulties to revalorize those from the technical and economic aspects, as both their properties and value to the industry were mostly unknown is one contribution aspect. Providing a new portrait of those materials and their properties helps the involved stakeholders make informed decisions on their stocks and processes and the potential for changing their business models or even investing in certain technologies in the future. By reducing the reliance on extracted materials for cement production, there is a potential to reduce harm from both extractive processes (less raw materials needed) and waste generation (less landfilling of GWM and similar byproducts).

Furthermore, although the research did not go into this sort of analysis, insights into the economic benefits that can result from the use of locally (Greater Region) available SCMs in certain circumstances providing comparable or improved performance to traditional OPC based products can also be a benefiting factor for both industry and consumers, for example with industrial partners investing in clay calcination kilns already in their cement production plants.

The research outcome also provided an evaluation tool that can be used by industrial actors (4.4 The pozzolanicity potential index) to assess in collaboration with academic or professional laboratories certain properties of the materials they wish to investigate and have a quick overview on their potential use as SCM.

8.2.3 Promoting sustainability and circularity

Beyond the technical feasibility, the use of SCMs with the conditions studied in project CO2REDRES and at least 13% of OPC CEM I substitution has been confirmed with an LCA study carried out in line with ISO 14040 and 14044 standards, to be a more sustainable option than traditional concrete across all studied categories, and not only carbon emissions. Nevertheless, the reduction of carbon emissions by partially replacing OPC with pozzolanic SCM is equally a gain in the climate change category. The formulations of the mixes discussed in section 3.4 show that the used substitution rate was of 20%. The LCA results show that mortars incorporating calcined clays can achieve substantial reductions in greenhouse gas emissions, with the largest gains coming from lower clinker use and decreased consumption of fossil fuels. Depending on the water saturation of the clays that can go up to 100%, more energy is needed to dry the materials. Nevertheless, even in the most energy-intensive scenarios, the substitution of clinker leads to a clear overall reduction in climate change impact indicators as demonstrated by the LCA scenarios.

The results show a substantial reduction in CO_2 emissions when clinker is replaced by these new mineral additions. For mortars incorporating calcined clays, the carbon footprint was reduced by approximately 30 to 40% compared to conventional mortars, depending on the initial moisture content and energy required for calcination.

The novel SCM studied in project CO2RERDRES are derived from industrial by-products, and studying their pozzolanicity promotes the circular use of these materials, reducing waste and conserving natural resources, for the quarries and the concrete industry respectively.

8.2.4 Contributions to regulatory and standardization efforts

The outcomes highlighted can be used to inform policy development since the research provides evidence-based insights that can help shape policies promoting the adoption of novel SCM in the construction sector, and later on project CO2REDSAP concluded that there are no policies in Luxembourg that relate generally or specifically to the use of SCM but are rather intersectional policies with the waste law or certain circularity strategies.

Regarding standardization, the characterization of the properties of the studied SCM in project CO2REDRES can add to the library of results and contributes to the development of industry standards and regulatory frameworks for their safe and effective use since the more data there is, and the more it resembles other widely used standardized materials, the higher the chances of its adoption.

8.3 Contributions to the field CO2REDSAP

8.3.1 Expanding academic knowledge and carrying it beyond

The nature of this research being interdisciplinary and borrowing concepts from two worlds of research – the qualitative and quantitative – expands the body of academic knowledge and introduces new methodologies (in both parts, such as the pozzolanicity ranking in CO2REDRES and the ontological element in CO2REDSAP). It also fosters holistic understandings that otherwise would not have been possible separately. Evidence-based solutions for SCMs and experience-based input from experts on circularity in the built environment work hand in hand not only to enrich present and future theoretical understandings and frameworks but also to provide actionable insights that can carry on to the industry's practice, policy development, and future research directions.

8.3.2 Seeing circularity through a new angle: the philosophical ontology lens approach.

The conceptual research framework of project CO2REDSAP attempts to takes into consideration how different ontologies influence the concept of circularity, from understanding to practice and implementation as explained in chapter 5. By looking at circularity through this angle, the discussion reveals how the nature of reality influences the applications of circularity and the degree to which solutions are holistic and systemic as opposed to punctual and remedial. Applying the concept of philosophical ontologies to conduct the research and analyze the outcomes - with human agency at the center - allows for advancing pragmatic solutions that can address the current challenges that transition, and change are facing (see Figure 79 for a system of solutions based on the mapped challenges).

8.3.3 Interdisciplinary insights: research on novel SCMs bridged with circularity as a concept.

By breaking down disciplinary silos, interdisciplinary research plays a crucial role in advancing circularity in construction by integrating knowledge from material science, engineering, sustainability science, policy, and social sciences. This holistic approach helps address a wider systemic aspect and an array of challenges of transitioning to a circular built environment such as the ones detailed in the data analysis chapter in section 6.1.1.1.

The interdisciplinary approach helped optimize material properties in a first step while considering real-world construction constraints in a second. Faced by a lack of industrial scaling of research outcome solutions, implementing circular construction practices requires insights from industrial ecology, architecture, chemistry and material science to design concepts etc. Furthermore, the identification of stakeholders can pave the way for fostering better and strategic connections between those, while showing that stakeholder engagement ensures that circular solutions align with all parties and create a ground of common interest. Additionally, integrating the policy part in the analysis can help support circularity without imposing impractical burdens to the sector by being incoherent or lacking a systemic vision.

8.3.4 Inspiration for future research

By identifying gaps and opportunities, the study could stimulate further exploration of regenerative circularity and what it means in pragmatic terms of integration into circular construction practices. As the literature starts to build up and different ontologies allied with a sense of awareness and urgency inspire stakeholders and decision makers alike to shift ways of thinking, this research becomes the more valuable.

8.4 Suggestions for future research

Future research in SCMs could explore innovative techniques to improve the pozzolanic reactivity of diverse materials by focusing on optimizing blended mixtures by varying particle sizes and chemical compositions to enhance long-term durability and environmental performance. Research can also take the direction of trying to replicate properties that are important and known in conventional concrete especially in terms of resistance to adverse effects and the long-term behavior. There is also a promising path in using machine learning algorithms to predict performance based on experimental data, thereby accelerating the discovery of novel SCM combinations with improved sustainability and mechanical properties.

As for the qualitative research part, a workshop for validating the insights generated through the interview data analyses and putting in place actions that empower the suggested model of solutions as well as suggestions to pragmatic changes in certain policies could really reap the benefits of this study in ways that exceed the initial research objectives.

8.5 Final considerations

In the context of the built environment, the shift towards sustainability through circularity can be approached with a mindset of addition rather than replacement. Just as the sector faces the challenge of balancing innovation with ongoing entrenched conventional attributes, the adoption of circular practices will need to progress incrementally and pragmatically. As the outcomes of this research pointed, it will not be a straightforward or linear transition, but rather one that unfolds in stages, driven by diverse technologies, regional needs, and varying paces of change influenced by innovation, stakeholders, and policy together. The research data reveals that national policy could encourage nature-positive practices by aligning economic policies with circular economy principles, such as adapting taxation, subsidies, and rules that impact this aspect of construction. Expanding policy targets beyond waste collection and a positivist ontological approach, along with developing monitoring and measuring frameworks both qualitatively and quantitatively, may help accelerate the transition to a circular economy for sustainable transformation, supported by precise and valuable data and metrics. In addition, investing in research, innovation, and public funding can drive systemic solutions, while revising key policies like the ones mentioned in the result analyses chapter also have the potential to strengthen circular economy practices in the built environment. As the built environment adapts to ways of circularity, stakeholders are invited to embrace this multidimensional process, where the incorporation of sustainable practices will occur alongside existing methods, rather than replacing them entirely. This approach ensures that the transition is realistic and resilient, addressing systemic aspects, as well as the varied demands of the built environment. A pragmatic, flexible path is essential for achieving meaningful progress in the move toward a circular built environment be it the pathway or the destination.

Part V | References

9 References

[1] United Nations Environment Programme (UNEP), 'Buildings and Climate Change Summary for Decision-Makers', 2009. Accessed: May 30, 2023. [Online]. Available: https://wedocs.unep.org/20.500.11822/32152

[2] United Nations Environment Programme (UNEP), 'Global Resource Outlook', 2024. Accessed: Feb. 13, 2025. [Online]. Available: https://www.unep.org/resources/Global-Resource-Outlook-2024

[3] CEMBUREAU, 'Cementing the European Green Deal: Carbon Neutrality Roadmap', 2024.

[4] J. Hart, K. Adams, J. Giesekam, D. D. Tingley, and F. Pomponi, 'Barriers and drivers in a circular economy: the case of the built environment', *Procedia CIRP*, vol. 80, pp. 619–624, 2019, doi: 10.1016/j.procir.2018.12.015.

[5] A. Luciano, L. Cutaia, P. Altamura, and E. Penalvo, 'Critical issues hindering a widespread construction and demolition waste (CDW) recycling practice in EU countries and actions to undertake: The stakeholder's perspective', *Sustain Chem Pharm*, vol. 29, p. 100745, Oct. 2022, doi: 10.1016/J.SCP.2022.100745.

[6] S. Giorgi, M. Lavagna, K. Wang, M. Osmani, G. Liu, and A. Campioli, 'Drivers and barriers towards circular economy in the building sector: Stakeholder interviews and analysis of five European countries policies and practices', *J Clean Prod*, vol. 336, p. 130395, Feb. 2022, doi: 10.1016/J.JCLEPRO.2022.130395.

[7] J. Rockström *et al.*, 'A safe operating space for humanity', *Nature*, vol. 461, no. 7263, pp. 472–475, Sep. 2009, doi: 10.1038/461472a.

[8] K. Richardson *et al.*, 'Earth beyond six of nine planetary boundaries', *Sci Adv*, vol. 9, no. 37, Sep. 2023, doi: 10.1126/sciadv.adh2458.

[9] T. Parrique, *Ralentir ou Périr: L'économie de la décroissance*. 2022.

[10] J. Monteiro and S. Roussanaly, 'CCUS scenarios for the cement industry: Is CO2utilization feasible?', *Journal of CO2 Utilization*, vol. 61, Jul. 2022, doi: 10.1016/j.jcou.2022.102015.

[11] D. L. Summerbell, C. Y. Barlow, and J. M. Cullen, ‘Potential reduction of carbon emissions by performance improvement: A cement industry case study’, *J Clean Prod*, vol. 135, pp. 1327–1339, Nov. 2016, doi: 10.1016/j.jclepro.2016.06.155.

[12] IEA, ‘Cement’, Paris, 2021. Accessed: Feb. 01, 2022. [Online]. Available: https://www.iea.org/reports/cement

[13] P. Van Den Heede and N. De Belie, ‘Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations’, *Cem Concr Compos*, vol. 34, no. 4, pp. 431–442, Apr. 2012, doi: 10.1016/j.cemconcomp.2012.01.004.

[14] J. M. Paris, J. G. Roessler, C. C. Ferraro, H. D. Deford, and T. G. Townsend, ‘A review of waste products utilized as supplements to Portland cement in concrete’, May 10, 2016, *Elsevier Ltd*. doi: 10.1016/j.jclepro.2016.02.013.

[15] A. Tironi, M. A. Trezza, A. N. Scian, and E. F. Irassar, ‘Assessment of pozzolanic activity of different calcined clays’, *Cem Concr Compos*, vol. 37, no. 1, pp. 319–327, Mar. 2013, doi: 10.1016/j.cemconcomp.2013.01.002.

[16] A. Bakolas, E. Aggelakopoulou, A. Moropoulou, and S. Anagnostopoulou, ‘Evaluation of pozzolanic activity and physicomechanical characteristics in metakaolin-lime pastes’, *J Therm Anal Calorim*, vol. 84, no. 1, pp. 157–163, Apr. 2006, doi: 10.1007/s10973-005-7262-y.

[17] P. Suraneni and J. Weiss, ‘Examining the pozzolanicity of supplementary cementitious materials using isothermal calorimetry and thermogravimetric analysis’, *Cem Concr Compos*, vol. 83, pp. 273–278, Oct. 2017, doi: 10.1016/j.cemconcomp.2017.07.009.

[18] R. Siddique and M. I. Khan, *Supplementary Cementing Materials*, vol. 37. in Engineering Materials, vol. 37. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011. doi: 10.1007/978-3-642-17866-5.

[19] K. Scrivener, ‘A Breakthrough Technology to Reduce CO2-emissions From Cementitious Materials’, in *International VDZ congress.*, Dusseldorf, 2018.

[20] M. Ahmaruzzaman, 'A review on the utilization of fly ash', *Prog Energy Combust Sci*, vol. 36, no. 3, pp. 327–363, Jun. 2010, doi: 10.1016/J.PECS.2009.11.003.

[21] C. Farinha, J. de Brito, and M. Do Veiga, 'Wastes', *Eco-Efficient Rendering Mortars*, pp. 27–52, Jan. 2021, doi: 10.1016/B978-0-12-818494-3.00003-9.

[22] A. Tironi, M. A. Trezza, E. F. Irassar, and A. N. Scian, 'Thermal Treatment of Kaolin: Effect on the Pozzolanic Activity', *Procedia Materials Science*, vol. 1, pp. 343–350, Jan. 2012, doi: 10.1016/J.MSPRO.2012.06.046.

[23] G. Bumanis, L. Vitola, L. Stipniece, J. Locs, A. Korjakins, and D. Bajare, 'Evaluation of Industrial by-products as pozzolans: A road map for use in concrete production', *Case Studies in Construction Materials*, vol. 13, Dec. 2020, doi: 10.1016/j.cscm.2020.e00424.

[24] V. Thapa and D. Waldmann, 'Binary blended cement pastes and concrete using gravel wash mud (GWM) powders', *Constr Build Mater*, vol. 302, Oct. 2021, doi: 10.1016/j.conbuildmat.2021.124225.

[25] V. B. Thapa, D. Waldmann, and C. Simon, 'Gravel wash mud, a quarry waste material as supplementary cementitious material (SCM)', *Cem Concr Res*, vol. 124, Oct. 2019, doi: 10.1016/j.cemconres.2019.105833.

[26] A. Tironi, F. Cravero, A. N. Scian, and E. F. Irassar, 'Pozzolanic activity of calcined halloysite-rich kaolinitic clays', *Appl Clay Sci*, vol. 147, pp. 11–18, Oct. 2017, doi: 10.1016/j.clay.2017.07.018.

[27] V. B. Thapa and D. Waldmann, 'Performance of lime-metakaolin pastes using gravel wash mud (GWM)', *Cem Concr Compos*, vol. 114, Nov. 2020, doi: 10.1016/j.cemconcomp.2020.103772.

[28] S. Donatello, M. Tyrer, and C. R. Cheeseman, 'Comparison of test methods to assess pozzolanic activity', *Cem Concr Compos*, vol. 32, no. 2, pp. 121–127, Feb. 2010, doi: 10.1016/J.CEMCONCOMP.2009.10.008.

[29] M. Frias Rojas and M. I. Sánchez de Rojas Gómez, 'Artificial pozzolans in eco-efficient concrete', *Eco-Efficient Concrete*, pp. 105–122, Jan. 2013, doi: 10.1533/9780857098993.2.105.

[30] G. Georgopoulos, E. Badogiannis, S. Tsivilis, and M. Perraki, 'Thermally and mechanically treated Greek palygorskite clay as a pozzolanic material', *Appl Clay Sci*, vol. 215, Dec. 2021.

[31] S. Funtowicz and J. Ravetz, 'Science for the post-normal Age', *Futures*, Sep. 1993, doi: https://doi.org/10.1016/0016-3287(93)90022-L.

[32] S. Pérez López, J. Manuel Montes Peón, and C. José Vazquez Ordás, 'Organizational learning as a determining factor in business performance', *The Learning Organization*, vol. 12, no. 3, pp. 227–245, Jun. 2005, doi: 10.1108/09696470510592494.

[33] R. V. Thomas, D. G. Nair, and B. Enserink, 'Conceptual framework for sustainable construction', *Architecture, Structures and Construction*, vol. 3, no. 1, pp. 129–141, Apr. 2023, doi: 10.1007/s44150-023-00087-8.

[34] E. F. M. Sobral, D. S. G. Junior, J. C. F. De Oliveira, and F. J. C. De Melo, 'Assessment of the construction industry market: a study of the barriers and drivers of sustainability practices', *International Journal of Sustainable Society*, vol. 15, no. 2, p. 1, 2023, doi: 10.1504/IJSSOC.2023.10051484.

[35] P. Tunji-Olayeni, K. Kajimo-Shakantu, T. O. Ayodele, and O. Babalola, 'Promoting construction for sustainability transformation: the perspective of institutional theory', *International Journal of Building Pathology and Adaptation*, Apr. 2023, doi: 10.1108/IJBPA-07-2022-0104.

[36] A. E. Oke *et al.*, 'A quantitative assessment of key drivers for environmental economic practices adoption for sustainable development', *Sustainable Development*, vol. 31, no. 5, pp. 3579–3594, Oct. 2023, doi: 10.1002/sd.2612.

[37] V. Levesque and SUST 501 Students, 'Interdisciplinary and transdisciplinary approaches', in *Sustainability Methods & Perspectives*, Pressbooks.

[38] K. Huutoneimi and P. Taipo, 'Transdisciplinary Sustainability Studies', 2014.

[39] K. Charmaz, *Constructing Grounded Theory*, 2nd ed. Sage Publications Ltd, 2014.

[40] A. K. Samal, M. Panigrahi, R. I. Ganguly, and R. R. Dash, 'Historical Development of Construction Materials – From Stone Age to Modern Age', in *Development of Geopolymer from Pond Ash-Thermal Power Plant Waste: Novel Constructional Materials for Civil Engineers*, 2023, pp. 1–70. Accessed: Jan. 30, 2024. [Online]. Available: https://doi.org/10.1002/9781394167975.ch1

[41] A. Khitab and W. Anwar, 'Classical Building Materials', 2016, pp. 1–27. doi: 10.4018/978-1-5225-0344-6.ch001.

[42] 'Irish Concrete Society'. Accessed: Jan. 31, 2024. [Online]. Available: https://concrete.ie/about-concrete/history-of-concrete/

[43] Shyamali Griffiths, 'How to grow concrete', *Engineering & Technology*, vol. 17, pp. 44–47, 2022.

[44] J. Kwan, 'Scientists may have found magic ingredient behind ancient Rome's self-healing concrete', *Science*, Jan. 06, 2023. doi: 10.1126/science.adg5743.

[45] R. Mark and P. Hutchinson, 'On the Structure of the Roman Pantheon', *Art Bull*, vol. 68, no. 1, pp. 24–34, 1986, Accessed: Jan. 31, 2024. [Online]. Available: http://www.jstor.org/stable/3050861

[46] 'To Joseph Aspdin, of Leeds, in the County of York, Bricklayer, for his new invented improvement in the mode of producing an artificial stone', *J Franklin Inst*, vol. 1, no. 3, pp. 146–149, Mar. 1826, doi: 10.1016/S0016-0032(26)91571-8.

[47] J. F. Young, 'Portland Cements', in *Encyclopedia of Materials: Science and Technology*, Elsevier, 2001, pp. 7768–7773. doi: 10.1016/B0-08-043152-6/01398-X.

[48] T. Harrison, M. R. Jones, and D. Lawrence, 'The production of low energy cements', in *Lea's Chemistry of Cement and Concrete*, Elsevier, 2019, pp. 341–361. doi: 10.1016/B978-0-08-100773-0.00008-3.

[49] IEA, 'Technology Roadmap: Low-Carbon Transition in the Cement Industry', OECD, Paris, Apr. 2018. doi: 10.1787/9789264300248-en.

[50] M. L. Wilson and S. H. Kosmatka, *Design and Control of Concrete Mixtures*, 16th ed. Portland Cement Association , 2016.

[51] P. Hewlett, *Lea's Chemistry of Cement and Concrete*. Oxford: Elsevier Science & Technology.

[52] G. Moir, 'Cements', *Advanced Concrete Technology*, pp. 3–45, Jan. 2003, doi: 10.1016/B978-075065686-3/50277-9.

[53] A. B. Albert, B. A. Alabadan, C. F. Njoku, and M. O. Yusuf, 'The Potentials of Groundnut Shell Ash as Concrete Admixture', 2006. [Online]. Available: https://www.researchgate.net/publication/331804379

[54] V. K. Singh, 'Hydration and setting of Portland cement', *The Science and Technology of Cement and Other Hydraulic Binders*, pp. 423–466, Jan. 2023, doi: 10.1016/B978-0-323-95080-0.00012-1.

[55] R. Burg, 'Concrete Basics: Track Cement Chemistry to Help Predict Performance', *Concrete Construction*, 1993.

[56] T. Hirsch, T. Matschei, and D. Stephan, 'The hydration of tricalcium aluminate (Ca3Al2O6) in Portland cement-related systems: A review', *Cem Concr Res*, vol. 168, p. 107150, Jun. 2023, doi: 10.1016/J.CEMCONRES.2023.107150.

[57] Y. Tao, D. Wan, W. Zhang, F. Wang, and S. Hu, 'Intrinsic reactivity and dissolution characteristics of tetracalcium aluminoferrite', *Cem Concr Res*, vol. 146, p. 106485, Aug. 2021, doi: 10.1016/J.CEMCONRES.2021.106485.

[58] C. K. Y. Leung, 'Concrete as a Building Material', *Encyclopedia of Materials: Science and Technology*, pp. 1471–1479, Jan. 2001, doi: 10.1016/B0-08-043152-6/00267-9.

[59] E. M. Gartner, J. F. Young, D. A. DamidoT, and I. Jawed, 'Hydration of portland cement', in *Structure and Performance of Cements*, 2nd ed., Spon Press, 2002, pp. 57–113.

[60] Y. Lin, U. J. Alengaram, and Z. Ibrahim, 'Effect of treated and untreated rice husk ash, palm oil fuel ash, and sugarcane bagasse ash on the mechanical, durability, and microstructure characteristics of blended concrete – A

comprehensive review', Nov. 01, 2023, *Elsevier Ltd*. doi: 10.1016/j.jobe.2023.107500.

[61] H. M. Saleh and S. B. Eskander, 'Innovative cement-based materials for environmental protection and restoration', *New Materials in Civil Engineering*, pp. 613–641, Jan. 2020, doi: 10.1016/B978-0-12-818961-0.00018-1.

[62] J. W. Bullard *et al.*, 'Mechanisms of cement hydration', *Cem Concr Res*, vol. 41, no. 12, pp. 1208–1223, Dec. 2011, doi: 10.1016/J.CEMCONRES.2010.09.011.

[63] D. Kulisch, A. Katz, and S. Zhutovsky, 'Quantification of Residual Unhydrated Cement Content in Cement Pastes as a Potential for Recovery', *Sustainability (Switzerland)*, vol. 15, no. 1, Jan. 2023, doi: 10.3390/su15010263.

[64] P. C. Aïtcin, 'The Influence of the Water/Cement Ratio on the Sustainability of Concrete', in *Lea's Chemistry of Cement and Concrete*, Butterworth-Heinemann, 2019, pp. 807–826. doi: 10.1016/B978-0-08-100773-0.00017-4.

[65] J. M. Khatib, O. Baalbaki, and A. A. ElKordi, 'Metakaolin', *Waste and Supplementary Cementitious Materials in Concrete: Characterisation, Properties and Applications*, pp. 493–511, Jan. 2018, doi: 10.1016/B978-0-08-102156-9.00015-8.

[66] Z. T. Yao *et al.*, 'A comprehensive review on the applications of coal fly ash', *Earth Sci Rev*, vol. 141, pp. 105–121, Feb. 2015, doi: 10.1016/J.EARSCIREV.2014.11.016.

[67] Y. Jiang, T. C. Ling, C. Shi, and S. Y. Pan, 'Characteristics of steel slags and their use in cement and concrete—A review', *Resour Conserv Recycl*, vol. 136, pp. 187–197, Sep. 2018, doi: 10.1016/J.RESCONREC.2018.04.023.

[68] A. K. Dikshit, S. Gupta, S. K. Chaturvedi, and L. P. Singh, 'Usage of lime sludge waste from paper industry for production of Portland cement Clinker: Sustainable expansion of Indian cement industry', *Case Studies in Chemical and Environmental Engineering*, vol. 9, p. 100557, Jun. 2024, doi: 10.1016/J.CSCEE.2023.100557.

[69] N. Savadogo *et al.*, 'Hydration and physico-mechanical characterization of bottom ash-based cement', *Constr Build Mater*, vol. 434, p. 136679, Jul. 2024, doi: 10.1016/J.CONBUILDMAT.2024.136679.

[70] R. Roychand *et al.*, 'Recycling biosolids as cement composites in raw, pyrolyzed and ashed forms: A waste utilisation approach to support circular economy', *Journal of Building Engineering*, vol. 38, p. 102199, Jun. 2021, doi: 10.1016/J.JOBE.2021.102199.

[71] V. B. Thapa, D. Waldmann, J. F. Wagner, and A. Lecomte, 'Assessment of the suitability of gravel wash mud as raw material for the synthesis of an alkali-activated binder', *Appl Clay Sci*, vol. 161, pp. 110–118, Sep. 2018, doi: 10.1016/J.CLAY.2018.04.025.

[72] M. M. Madirisha, O. R. Dada, and B. D. Ikotun, 'Chemical fundamentals of geopolymers in sustainable construction', *Materials Today Sustainability*, vol. 27, p. 100842, Sep. 2024, doi: 10.1016/J.MTSUST.2024.100842.

[73] K. Scrivener *et al.*, 'Impacting factors and properties of limestone calcined clay cements (LC3)', *Green Mater*, vol. 7, no. 1, pp. 3–14, Mar. 2019, doi: 10.1680/jgrma.18.00029.

[74] R. V. Silva and J. Brito, 'Plastic wastes', *Waste and Supplementary Cementitious Materials in Concrete: Characterisation, Properties and Applications*, pp. 199–227, Jan. 2018, doi: 10.1016/B978-0-08-102156-9.00007-9.

[75] İ. B. Topçu and A. Unverdi, 'Scrap tires/crumb rubber', *Waste and Supplementary Cementitious Materials in Concrete: Characterisation, Properties and Applications*, pp. 51–77, Jan. 2018, doi: 10.1016/B978-0-08-102156-9.00002-X.

[76] M. Bacatelo, F. Capucha, P. Ferrão, F. Margarido, and J. Bordado, 'Carbon-neutral cement: The role of green hydrogen', *Int J Hydrogen Energy*, vol. 63, pp. 382–395, Apr. 2024, doi: 10.1016/J.IJHYDENE.2024.03.028.

[77] American Society for Testing and Materials, 'ASTM C-125. Standard terminology relating to concrete and concrete aggregates.'

[78] European Commitee for Standardization, ‘DIN EN 197-1:2000 Cement - Part 1: Composition, specifications and conformity criteria for common cements’.

[79] M. Ayub *et al.*, ‘Promoting sustainable cleaner production paradigms in palm oil fuel ash as an eco-friendly cementitious material: A critical analysis’, *J Clean Prod*, vol. 295, p. 126296, May 2021, doi: 10.1016/J.JCLEPRO.2021.126296.

[80] H. Wang, X. Liu, and Z. Zhang, ‘Pozzolanic activity evaluation methods of solid waste: A review’, *J Clean Prod*, vol. 402, p. 136783, May 2023, doi: 10.1016/J.JCLEPRO.2023.136783.

[81] V. K. Singh, ‘Classification of pozzolana and production of pozzolanic cements’, *The Science and Technology of Cement and Other Hydraulic Binders*, pp. 653–694, Jan. 2023, doi: 10.1016/B978-0-323-95080-0.00018-2.

[82] I. Sims and B. Brown, ‘Concrete Aggregates’, *Lea's Chemistry of Cement and Concrete*, pp. 907–1015, Jan. 1998, doi: 10.1016/B978-075066256-7/50028-X.

[83] F. Pacheco-Torgal and S. Jalali, ‘Cementitious building materials reinforced with vegetable fibres: A review’, *Constr Build Mater*, vol. 25, no. 2, pp. 575–581, Feb. 2011, doi: 10.1016/J.CONBUILDMAT.2010.07.024.

[84] M. D. Rout, S. Biswas, K. Shubham, and A. K. Sinha, ‘A systematic review on performance of reclaimed asphalt pavement (RAP) as sustainable material in rigid pavement construction: Current status to future perspective’, *Journal of Building Engineering*, vol. 76, p. 107253, Oct. 2023, doi: 10.1016/J.JOBE.2023.107253.

[85] J. Ma, D. Wang, S. Zhao, P. Duan, and S. Yang, ‘Influence of particle morphology of ground fly ash on the fluidity and strength of cement paste’, *Materials*, vol. 14, no. 2, pp. 1–18, Jan. 2021, doi: 10.3390/ma14020283.

[86] B. Lothenbach, K. Scrivener, and R. D. Hooton, ‘Supplementary cementitious materials’, *Cem Concr Res*, vol. 41, no. 12, pp. 1244–1256, Dec. 2011, doi: 10.1016/J.CEMCONRES.2010.12.001.

[87] A. Seco *et al.*, ‘Types of Waste for the Production of Pozzolanic Materials – A Review’, in *Industrial Waste*, InTech, 2012. doi: 10.5772/36285.

[88] N. Lee, Y. Jeong, H. Kang, and J. Moon, 'Heat-induced acceleration of pozzolanic reaction under restrained conditions and consequent structural modification', *Materials*, vol. 13, no. 13, Jul. 2020, doi: 10.3390/ma13132950.

[89] W. Zhang, S. Wang, J. Ran, H. Lin, W. Kang, and J. Zhu, 'Research progress on the performance of circulating fluidized bed combustion ash and its utilization in China', *Journal of Building Engineering*, vol. 52, p. 104350, Jul. 2022, doi: 10.1016/J.JOBE.2022.104350.

[90] M. Singh, 'Coal bottom ash', *Waste and Supplementary Cementitious Materials in Concrete: Characterisation, Properties and Applications*, pp. 3–50, Jan. 2018, doi: 10.1016/B978-0-08-102156-9.00001-8.

[91] French norm NF-P 18-513, 'Chapelle Test Modified (Annexe A)', 2009.

[92] S. Hollanders, R. Adriaens, J. Skibsted, Ö. Cizer, and J. Elsen, 'Pozzolanic reactivity of pure calcined clays', *Appl Clay Sci*, vol. 132–133, pp. 552–560, Nov. 2016, doi: 10.1016/J.CLAY.2016.08.003.

[93] E. Ferraz, S. Andrejkovičová, W. Hajjaji, A. L. Velosa, A. S. Silva, and F. Rocha, 'Pozzolanic activity of metakaolins by the French standard of the modified Chapelle test: A direct methodology', *Acta Geodynamica et Geomaterialia*, vol. 12, no. 3, pp. 289–298, Sep. 2015, doi: 10.13168/AGG.2015.0026.

[94] F. Avet, R. Snellings, A. Alujas Diaz, M. Ben Haha, and K. Scrivener, 'Development of a new rapid, relevant and reliable (R3) test method to evaluate the pozzolanic reactivity of calcined kaolinitic clays', *Cem Concr Res*, vol. 85, pp. 1–11, Jul. 2016, doi: 10.1016/j.cemconres.2016.02.015.

[95] European Committee for Standardization, 'DIN EN 197-5:2011, Methods of testing cement. Part 5, Pozzolanicity test for pozzolanic cement'.

[96] A. Tironi, M. A. Trezza, A. N. Scian, and E. F. Irassar, 'Assessment of pozzolanic activity of different calcined clays', *Cem Concr Compos*, vol. 37, no. 1, pp. 319–327, Mar. 2013, doi: 10.1016/J.CEMCONCOMP.2013.01.002.

[97] M. Šídlová, R. Šulc, F. Škvára, K. Pulcová, P. Formáček, and R. Snop, 'Pozzolanic activity of stockpile ash: Comparison of test methods', *Case*

Studies in Construction Materials, vol. 19, p. e02396, Dec. 2023, doi: 10.1016/J.CSCM.2023.E02396.

[98] G. Malata and E. Tkaczewska, 'Application of thermal methods in the studies of potential pozzolanic reactivity of attapulgite and sepiolite', *J Therm Anal Calorim*, vol. 148, no. 15, pp. 7611–7622, Aug. 2023, doi: 10.1007/s10973-023-12257-3.

[99] V. Kasselouri, C. Ftikos, and G. Parissakis, 'DTA-TG study on the Ca(OH)2 - pozzolan reaction in cement pastes hydrated up to three years', *Cem Concr Res*, vol. 13, no. 5, pp. 649–654, Sep. 1983, doi: 10.1016/0008-8846(83)90054-6.

[100] P. Suraneni and J. Weiss, 'Examining the pozzolanicity of supplementary cementitious materials using isothermal calorimetry and thermogravimetric analysis', *Cem Concr Compos*, vol. 83, pp. 273–278, Oct. 2017, doi: 10.1016/J.CEMCONCOMP.2017.07.009.

[101] C. Vizcayno, R. M. de Gutiérrez, R. Castello, E. Rodriguez, and C. E. Guerrero, 'Pozzolan obtained by mechanochemical and thermal treatments of kaolin', *Appl Clay Sci*, vol. 49, no. 4, pp. 405–413, Aug. 2010, doi: 10.1016/J.CLAY.2009.09.008.

[102] S. Hollanders, 'Mineralogical study of the pozzolanic properties of calcined clays', 2017.

[103] Y. Senhadji, G. Escadeillas, H. Khelafi, M. Mouli, and A. S. Benosman, 'Evaluation of natural pozzolan for use as supplementary cementitious material', *European Journal of Environmental and Civil Engineering*, vol. 16, no. 1, pp. 77–96, Jan. 2012, doi: 10.1080/19648189.2012.667692.

[104] C. Patil, M. Manjunath, S. Hosamane, S. Bandekar, and R. Athani, 'Pozzolonic activity and strength activity index of bagasse ash and fly ash blended cement mortar', *Mater Today Proc*, vol. 42, pp. 1456–1461, Jan. 2021, doi: 10.1016/J.MATPR.2021.01.251.

[105] American Society for Testing and Materials, 'ASTM C-618. Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete', 2005.

[106] European Committee for standardization, 'DIN EN 196-1:2016-11, Methods of Testing Cement - Part 1: Determination of Strength', 2016.

[107] O. Linderoth, L. Wadsö, and D. Jansen, 'Long-term cement hydration studies with isothermal calorimetry', *Cem Concr Res*, vol. 141, p. 106344, Mar. 2021, doi: 10.1016/J.CEMCONRES.2020.106344.

[108] S. Velázquez, J. M. Monzó, M. V. Borrachero, and J. Payá, 'Assessment of pozzolanic activity using methods based on the measurement of electrical conductivity of suspensions of portland cement and pozzolan', *Materials*, vol. 7, no. 11, pp. 7533–7547, 2014, doi: 10.3390/ma7117533.

[109] M. P. Luxán, F. Madruga, and J. Saavedra, 'Rapid evaluation of pozzolanic activity of natural products by conductivity measurement', *Cem Concr Res*, vol. 19, no. 1, pp. 63–68, Jan. 1989, doi: 10.1016/0008-8846(89)90066-5.

[110] R. Snellings, G. Mertens, and J. Elsen, 'Supplementary Cementitious Materials', *Rev Mineral Geochem*, vol. 74, no. 1, pp. 211–278, Jan. 2012, doi: 10.2138/rmg.2012.74.6.

[111] A. A. Jhatial, I. Nováková, and E. Gjerløw, 'A Review on Emerging Cementitious Materials, Reactivity Evaluation and Treatment Methods', Feb. 01, 2023, *MDPI*. doi: 10.3390/buildings13020526.

[112] J. E. Rossen, 'Composition and morphology of C-A-S-H in pastes of alite and cement blended with supplementary cementitious materials', EFPL, 2014.

[113] R. Siddique and M. Iqbal Khan, 'Fly Ash', 2011, pp. 1–66. doi: 10.1007/978-3-642-17866-5_1.

[114] A. K. Ram and S. Mohanty, 'State of the art review on physiochemical and engineering characteristics of fly ash and its applications', Dec. 01, 2022, *Springer International Publishing*. doi: 10.1007/s40789-022-00472-6.

[115] K. Sideris, H. Justnes, M. Soutsos, and T. Sui, 'Fly Ash', 2018, pp. 55–98. doi: 10.1007/978-3-319-70606-1_2.

[116] E. Khankhaje, T. Kim, H. Jang, C. S. Kim, J. Kim, and M. Rafieizonooz, 'Properties of pervious concrete incorporating fly ash as partial replacement of cement: A review', *Developments in the Built Environment*, vol. 14, p. 100130, Apr. 2023, doi: 10.1016/J.DIBE.2023.100130.

[117] R. Siddique and M. Iqbal Khan, 'Silica Fume', 2011, pp. 67–119. doi: 10.1007/978-3-642-17866-5_2.

[118] R. Siddique and M. Iqbal Khan, 'Ground Granulated Blast Furnace Slag', 2011, pp. 121–173. doi: 10.1007/978-3-642-17866-5_3.

[119] R. Jaskulski, D. Jóźwiak-Niedźwiedzka, and Y. Yakymechko, 'Calcined clay as supplementary cementitious material', Nov. 01, 2020, *MDPI AG*. doi: 10.3390/ma13214734.

[120] R. Siddique and M. Iqbal Khan, 'Metakaolin', in *Waste Materials and By-Products in Concrete.*, 2011, pp. 175–230. doi: 10.1007/978-3-642-17866-5_4.

[121] R. Sposito, N. Beuntner, and K.-C. Thienel, 'Characteristics of components in calcined clays and their influence on the efficiency of superplasticizers', *Cem Concr Compos*, vol. 110, p. 103594, Jul. 2020, doi: 10.1016/j.cemconcomp.2020.103594.

[122] H. Paiva, A. Velosa, P. Cachim, and V. M. Ferreira, 'Effect of metakaolin dispersion on the fresh and hardened state properties of concrete', *Cem Concr Res*, vol. 42, no. 4, pp. 607–612, Apr. 2012, doi: 10.1016/j.cemconres.2012.01.005.

[123] J. M. Huggett, 'Clay Minerals', *Reference Module in Earth Systems and Environmental Sciences*, Jan. 2015, doi: 10.1016/B978-0-12-409548-9.09519-1.

[124] Science Learning Hub at The University of Waikato, 'What is Clay?' Accessed: Jun. 22, 2024. [Online]. Available: https://www.sciencelearn.org.nz/resources/1771-what-is-clay

[125] M. Siline and B. Mehsas, 'Effect of increasing the Blaine fineness of Metakaolin on its chemical reactivity', *Journal of Building Engineering*, vol. 56, p. 104778, Sep. 2022, doi: 10.1016/J.JOBE.2022.104778.

[126] C. He, E. Makovicky, and B. Osbæck, 'Thermal stability and pozzolanic activity of raw and calcined mixed-layer mica/smectite', *Appl Clay Sci*, vol. 17, no. 3–4, pp. 141–161, Sep. 2000, doi: 10.1016/S0169-1317(00)00011-9.

[127] D. Zheng, X. Liang, H. Cui, W. Tang, W. Liu, and D. Zhou, 'Study of performances and microstructures of mortar with calcined low-grade clay', *Constr Build Mater*, vol. 327, p. 126963, Apr. 2022, doi: 10.1016/J.CONBUILDMAT.2022.126963.

[128] T. Ni, F. Xu, C. Gao, Y. Yang, W. Ma, and D. Kong, 'Chemical activation of pozzolanic activity of sludge incineration ash and application as row bonding materials for pervious ecological brick', *Constr Build Mater*, vol. 329, p. 127199, Apr. 2022, doi: 10.1016/J.CONBUILDMAT.2022.127199.

[129] S. Ahmari and L. Zhang, 'The properties and durability of mine tailings-based geopolymeric masonry blocks', *Eco-efficient Masonry Bricks and Blocks: Design*, *Properties and Durability*, pp. 273–287, Dec. 2014, doi: 10.1016/B978-1-78242-305-8.00013-9.

[130] B. Karim, S. Malika Mansour, M. Tahar Abadlia, K. Bekkour, and I. Messaoudene, 'Improvement of Rheological behaviour of Cement Pastes by Incorporating Metakaolin', 2010. [Online]. Available: http://www.eurojournals.com/ejsr.htm

[131] S. Earle, 'Clay Minerals', in *Environmental Geology*, 2021.

[132] I. Sánchez, I. S. de Soto, M. Casas, R. Vigil de la Villa, and R. García-Giménez, 'Evolution of Metakaolin Thermal and Chemical Activation from Natural Kaolin', *Minerals*, vol. 10, no. 6, p. 534, Jun. 2020, doi: 10.3390/min10060534.

[133] B. Sabir, S. Wild, and J. Bai, 'Metakaolin and calcined clays as pozzolans for concrete: a review', *Cem Concr Compos*, vol. 23, no. 6, pp. 441–454, Dec. 2001, doi: 10.1016/S0958-9465(00)00092-5.

[134] A. Z. Khalifa *et al.*, 'Advances in alkali-activation of clay minerals', *Cem Concr Res*, vol. 132, p. 106050, Jun. 2020, doi: 10.1016/j.cemconres.2020.106050.

[135] R. L. Frost, É. Makó, J. Kristóf, E. Horváth, and J. T. Kloprogge, 'Mechanochemical Treatment of Kaolinite', *J Colloid Interface Sci*, vol. 239, no. 2, pp. 458–466, Jul. 2001, doi: 10.1006/JCIS.2001.7591.

[136] B. Ilić, V. Radonjanin, M. Malešev, M. Zdujić, and A. Mitrović, 'Effects of mechanical and thermal activation on pozzolanic activity of kaolin containing mica', *Appl Clay Sci*, vol. 123, pp. 173–181, Apr. 2016, doi: 10.1016/j.clay.2016.01.029.

[137] M. Saad Morsy, S. A. Abo El-Enein, and G. B. Hanna, 'Microstructure and hydration characteristics of artificial pozzolana-cement pastes containing burnt kaolinite clay', *Cem Concr Res*, vol. 27, no. 9, pp. 1307–1312, Sep. 1997, doi: 10.1016/S0008-8846(97)00122-1.

[138] C. Vizcayno, R. M. de Gutiérrez, R. Castello, E. Rodriguez, and C. E. Guerrero, 'Pozzolan obtained by mechanochemical and thermal treatments of kaolin', *Appl Clay Sci*, vol. 49, no. 4, pp. 405–413, Aug. 2010, doi: 10.1016/J.CLAY.2009.09.008.

[139] A. Alujas Diaz *et al.*, 'Properties and occurrence of clay resources for use as supplementary cementitious materials: a paper of RILEM TC 282-CCL', *Mater Struct*, vol. 55, no. 5, p. 139, Jun. 2022, doi: 10.1617/s11527-022-01972-2.

[140] Normes Francaises et Europeennes, 'NF P18-513: Pozzolanic addition for concrete - Metakaolin - Definitions, specifications and conformity criteria', 2012.

[141] A. Mitrović and M. Zdujić, 'Preparation of pozzolanic addition by mechanical treatment of kaolin clay', *Int J Miner Process*, vol. 132, pp. 59–66, Nov. 2014, doi: 10.1016/J.MINPRO.2014.09.004.

[142] C. Vizcayno, R. M. de Gutiérrez, R. Castello, E. Rodriguez, and C. E. Guerrero, 'Pozzolan obtained by mechanochemical and thermal treatments of kaolin',

Appl Clay Sci, vol. 49, no. 4, pp. 405–413, Aug. 2010, doi: 10.1016/J.CLAY.2009.09.008.

[143] D. Ouyang, W. Xu, T. Y. Lo, and J. F. C. Sham, 'Increasing mortar strength with the use of activated kaolin by-products from paper industry', *Constr Build Mater*, vol. 25, no. 4, pp. 1537–1545, Apr. 2011, doi: 10.1016/J.CONBUILDMAT.2010.08.012.

[144] F. Wang *et al.*, 'Metakaolin', 2018, pp. 153–179. doi: 10.1007/978-3-319-70606-1_5.

[145] E. Badogiannis, G. Kakali, G. Dimopoulou, E. Chaniotakis, and S. Tsivilis, 'Metakaolin as a main cement constituent. Exploitation of poor Greek kaolins', *Cem Concr Compos*, vol. 27, no. 2, pp. 197–203, Feb. 2005, doi: 10.1016/J.CEMCONCOMP.2004.02.007.

[146] D. Waldmann and V. B. Thapa, 'A short review on alkali-activated binders and geopolymer binders', 2018. [Online]. Available: https://api.semanticscholar.org/CorpusID:55907982

[147] M. Nasir, A. H. Mahmood, and A. A. Bahraq, 'History, recent progress, and future challenges of alkali-activated binders – An overview', *Constr Build Mater*, vol. 426, p. 136141, May 2024, doi: 10.1016/j.conbuildmat.2024.136141.

[148] A. Palomo, M. W. Grutzeck, and M. T. Blanco, 'Alkali-activated fly ashes', *Cem Concr Res*, vol. 29, no. 8, pp. 1323–1329, Aug. 1999, doi: 10.1016/S0008-8846(98)00243-9.

[149] J.-F. Wagner, 'Alkali activation of gravel wash mud with KOH and NaOH', Nov. 2019.

[150] K. Kukemilks and J.-F. Wagner, 'Low CO2 emission cement from alkali-activated gravel wash mud and quartzite dust', *MATEC Web of Conferences*, vol. 403, p. 06003, Sep. 2024, doi: 10.1051/matecconf/202440306003.

[151] L. M. Vizcaíno-Andrés, S. Sánchez-Berriel, S. Damas-Carrera, A. Pérez-Hernández, K. L. Scrivener, and J. F. Martirena-Hernández, 'Industrial trial to

produce a low clinker, low carbon cement', *Materiales de Construcción*, vol. 65, no. 317, p. e045, Mar. 2015, doi: 10.3989/mc.2015.00614.

[152] École Polytechnique Fédérale de Lausanne, 'Limestone Calcined Clay Cement LC3', What is LC3?

[153] S. Barbhuiya, J. Nepal, and B. B. Das, 'Properties, compatibility, environmental benefits and future directions of limestone calcined clay cement (LC3) concrete: A review', *Journal of Building Engineering*, vol. 79, p. 107794, Nov. 2023, doi: 10.1016/j.jobe.2023.107794.

[154] S. Sánchez Berriel *et al.*, 'Assessing the environmental and economic potential of Limestone Calcined Clay Cement in Cuba', *J Clean Prod*, vol. 124, pp. 361–369, Jun. 2016, doi: 10.1016/j.jclepro.2016.02.125.

[155] C. Salvi Malacarne, M. Rubens Cardoso da Silva, S. Danieli, V. Gonçalves Maciel, and A. Paula Kirchheim, 'Environmental and technical assessment to support sustainable strategies for limestone calcined clay cement production in Brazil', *Constr Build Mater*, vol. 310, p. 125261, Dec. 2021, doi: 10.1016/j.conbuildmat.2021.125261.

[156] A. A. Díaz, R. S. Almenares Reyes, F. A. Carratalá, and J. F. Martirena Hernández, 'Proposal of a Methodology for the Preliminary Assessment of Kaolinitic Clay Deposits as a Source of SCMs', 2018, pp. 29–34. doi: 10.1007/978-94-024-1207-9_5.

[157] D. H. Meadows, D. L. Meadows, J. • Rgen, R. William, and W. Behrens Ill, 'The Limits to Growth. A report for the Club of Rome's project on the predicament of mankind.', 1972. Accessed: Jan. 18, 2024. [Online]. Available: https://www.clubofrome.org/publication/the-limits-to-growth/

[158] M. Calisto Friant, W. J. V. Vermeulen, and R. Salomone, 'Transition to a Sustainable Circular Society: More than Just Resource Efficiency', *Circular Economy and Sustainability*, 2023, doi: 10.1007/s43615-023-00272-3.

[159] E. C. Rada, 'Origins of the Concept of Circular Economy and its Evolution', *CONECT. International Scientific Conference of Environmental and Climate Technologies*, p. 141, May 2023, doi: 10.7250/conect.2023.110.

[160] A. Tuladhar, K. Iatridis, and D. Dimov, 'History and evolution of the circular economy and circular economy business models', *Circular Economy and Sustainability: Volume 1: Management and Policy*, pp. 87–106, Jan. 2022, doi: 10.1016/B978-0-12-819817-9.00031-4.

[161] J. C. J. M. Van Den Bergh, 'Robert Ayres, ecological economics and industrial ecology', 2013, *Elsevier B.V.* doi: 10.1016/j.eist.2013.09.008.

[162] R. U. Ayres, 'The second law, the fourth law, recycling and limits to growth', *Ecological Economics*, vol. 29, no. 3, pp. 473–483, Jun. 1999, doi: 10.1016/S0921-8009(98)00098-6.

[163] W. McDonough and M. Braungart, *Cradle to Cradle: Remaking the Way We Make Things*. 2002.

[164] A. Mavropoulos and A. W. Nilsen, *Industry 4.0 and circular economy: Towards a wasteless future or a wasteful planet?* 2020.

[165] British Standards Institution, 'BS 8001:2017 Framework for implementing the principles of the circular economy in organizations.', 2017.

[166] Ellen MacArthur Foundation, 'What is a circular economy?' Accessed: Feb. 03, 2023. [Online]. Available: https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

[167] F. Figge, A. S. Thorpe, and M. Gutberlet, 'Definitions of the circular economy: Circularity matters', *Ecological Economics*, vol. 208, p. 107823, Jun. 2023, doi: 10.1016/j.ecolecon.2023.107823.

[168] J. Kirchherr, D. Reike, and M. Hekkert, 'Conceptualizing the circular economy: An analysis of 114 definitions', *Resour Conserv Recycl*, vol. 127, pp. 221–232, Dec. 2017, doi: 10.1016/J.RESCONREC.2017.09.005.

[169] J. Korhonen, A. Honkasalo, and J. Seppälä, 'Circular Economy: The Concept and its Limitations', *Ecological Economics*, vol. 143, pp. 37–46, Jan. 2018, doi: 10.1016/J.ECOLECON.2017.06.041.

[170] M. J. Ávila-Gutiérrez, A. Martín-Gómez, F. Aguayo-González, and A. Córdoba-Roldán, 'Standardization Framework for Sustainability from Circular Economy 4.0', *Sustainability*, vol. 11, no. 22, p. 6490, Nov. 2019, doi: 10.3390/su11226490.

[171] H. Corvellec, A. F. Stowell, and N. Johansson, 'Critiques of the circular economy', *J Ind Ecol*, vol. 26, no. 2, pp. 421–432, Apr. 2022, doi: 10.1111/jiec.13187.

[172] A. Murray, K. Skene, and K. Haynes, 'The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context', *Journal of Business Ethics*, vol. 140, no. 3, pp. 369–380, Feb. 2017, doi: 10.1007/s10551-015-2693-2.

[173] C. Schulz, R. E. Hjaltadóttir, and P. Hild, 'Practising circles: Studying institutional change and circular economy practices', *J Clean Prod*, vol. 237, p. 117749, Nov. 2019, doi: 10.1016/j.jclepro.2019.117749.

[174] N. U. Blum, M. Haupt, and C. R. Bening, 'Why "Circular" doesn't always mean "Sustainable"', *Resour Conserv Recycl*, vol. 162, p. 105042, Nov. 2020, doi: 10.1016/j.resconrec.2020.105042.

[175] M. Haupt, T. Kägi, and S. Hellweg, 'Modular life cycle assessment of municipal solid waste management', *Waste Management*, vol. 79, pp. 815–827, Sep. 2018, doi: 10.1016/J.WASMAN.2018.03.035.

[176] T. Bosschaert, 'Circularity is not sustainability', in *The Impossibilities of the Circular Economy*, Routledge, 2022, pp. 72–80. doi: 10.4324/9781003244196-9.

[177] F. Blomsma and G. Brennan, 'The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity', *J Ind Ecol*, vol. 21, no. 3, pp. 603–614, Jun. 2017, doi: 10.1111/jiec.12603.

[178] E. A. Inigo and V. Blok, ‘Strengthening the socio-ethical foundations of the circular economy: Lessons from responsible research and innovation’, *J Clean Prod*, vol. 233, pp. 280–291, Oct. 2019, doi: 10.1016/J.JCLEPRO.2019.06.053.

[179] A. Temesgen, V. Storsletten, and O. Jakobsen, ‘Circular Economy – Reducing Symptoms or Radical Change?’, *Philos Manag*, vol. 20, no. 1, pp. 37–56, Mar. 2021, doi: 10.1007/s40926-019-00112-1.

[180] J. Affolderbach, C. Schulz, and B. Braun, ‘Green building as urban climate change strategy’, in *Urban Book Series*, no. 9783319777085, Springer, 2018, pp. 3–14. doi: 10.1007/978-3-319-77709-2_1.

[181] D. Loorbach, N. Frantzeskaki, and F. Avelino, ‘Sustainability Transitions Research: Transforming Science and Practice for Societal Change’, Oct. 17, 2017, *Annual Reviews Inc.* doi: 10.1146/annurev-environ-102014-021340.

[182] Ministry of Energy and Spatial Planning, ‘Luxembourg in Transition’. Accessed: Aug. 03, 2024. [Online]. Available: https://luxembourgintransition.lu/en/international-consultation/

[183] S. Davari, M. Jaberi, A. Yousfi, and E. Poirier, ‘A Traceability Framework to Enable Circularity in the Built Environment’, *Sustainability (Switzerland)*, vol. 15, no. 10, May 2023, doi: 10.3390/su15108278.

[184] N. Zhang, K. Gruhler, and G. Schiller, ‘A review of spatial characteristics influencing circular economy in the built environment’, Apr. 01, 2023, *Springer Science and Business Media Deutschland GmbH*. doi: 10.1007/s11356-023-26326-5.

[185] European Comission, ‘Construction and Demolition Waste’. Accessed: Apr. 03, 2024. [Online]. Available: https://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en

[186] L. Bogoviku and D. Waldmann, ‘Experimental investigations on the interfacial bond strength of the adhered mortar paste to the new mortar paste in a recycled concrete matrix’, *Constr Build Mater*, vol. 347, p. 128509, Sep. 2022, doi: 10.1016/J.CONBUILDMAT.2022.128509.

[187] J. Vengadesh Marshall Raman and V. Ramasamy, 'Various treatment techniques involved to enhance the recycled coarse aggregate in concrete: A review', *Mater Today Proc*, vol. 45, pp. 6356–6363, Jan. 2021, doi: 10.1016/J.MATPR.2020.10.935.

[188] A. Tokareva, S. Kaassamani, and D. Waldmann, 'Fine demolition wastes as Supplementary cementitious materials for CO2 reduced cement production', *Constr Build Mater*, vol. 392, p. 131991, Aug. 2023, doi: 10.1016/J.CONBUILDMAT.2023.131991.

[189] S. Copeland and M. Bilec, 'Buildings as material banks using RFID and building information modeling in a circular economy', *Procedia CIRP*, vol. 90, pp. 143–147, 2020, doi: https://doi.org/10.1016/j.procir.2020.02.122.

[190] The Norwegian Green Building Council, 'Think twice before demolishing: Advice on carrying out a successful construction project without demolition', 2019. Accessed: Mar. 21, 2024. [Online]. Available: https://byggalliansen.no/wp-content/ uploads/2019/11/Think-twice-before-demolishing. pdf

[191] F. Heisel and S. Rau-Oberhuber, 'Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster', *J Clean Prod*, vol. 243, p. 118482, Jan. 2020, doi: 10.1016/J.JCLEPRO.2019.118482.

[192] P. Mhatre, V. Gedam, S. Unnikrishnan, and S. Verma, 'Circular economy in built environment – Literature review and theory development', Mar. 01, 2021, *Elsevier Ltd*. doi: 10.1016/j.jobe.2020.101995.

[193] L. Bogoviku and D. Waldmann, 'Modelling of mineral construction and demolition waste dynamics through a combination of geospatial and image analysis', *J Environ Manage*, vol. 282, Mar. 2021, doi: 10.1016/j.jenvman.2020.111879.

[194] M. Arora, F. Raspall, L. Cheah, and A. Silva, 'Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building

components', *Resour Conserv Recycl*, vol. 154, p. 104581, Mar. 2020, doi: 10.1016/J.RESCONREC.2019.104581.

[195] P. Junior and D. M. Franks, 'Construction materials and sustainable development', in *Routledge Handbook of the Extractive Industries and Sustainable Development*, 1st ed., London: Routledge, 2022, pp. 228–246. doi: 10.4324/9781003001317-14.

[196] N. Sharma and A. K. Jha, 'Overview of Eco-Friendly Construction Materials', 2021, pp. 111–118. doi: 10.1007/978-981-15-8820-4_11.

[197] S. N. C. M. Nasir, N. H. M. Y. Ariffin, N. M. Alwi, S. Aziz, N. 'Izzati M. Amin, and M. F. Maharimi, 'Pragmatic Consideration on Eco-Friendly Building Materials for Healthy Homes', 2023, pp. 319–338. doi: 10.4018/978-1-6684-8253-7.ch017.

[198] A. Friedman, 'Green and Healthy Materials', in *Fundamentals of Innovative Sustainable Homes Design and Construction*, Cham: Springer International Publishing, 2023, pp. 203–227. doi: 10.1007/978-3-031-35368-0_8.

[199] X. Zheng and Y. Cai, 'Transforming Innovation Systems into Innovation Ecosystems: The Role of Public Policy', *Sustainability (Switzerland)*, vol. 14, no. 12, Jun. 2022, doi: 10.3390/su14127520.

[200] J. Fodor, A. AKBARIEH, M. SCHÄFER, and F. N. TEFERLE, 'Sustainability assessment of a novel reusable and demountable steel-concrete composite floor system', in *ECPPM 2022 - eWork and eBusiness in Architecture, Engineering and Construction 2022*, CRC Press, 2023. [Online]. Available: https://www.taylorfrancis.com/chapters/edit/10.1201/9781003354222-1/sustainability-assessment-novel-reusable-demountable-steel-concrete-composite-floor-system-fodor-akbarieh-sch%C3%A4fer-teferle

[201] A. Romero and C. Odenbreit, 'Experimental investigation on novel shear connections for demountable steel-timber composite (STC) beams and flooring systems', *Eng Struct*, vol. 304, p. 117620, Apr. 2024, doi: 10.1016/J.ENGSTRUCT.2024.117620.

[202] H. Eslami, L. B. Jayasinghe, and D. Waldmann, 'Experimental and numerical study on shear behavior of a demountable CLT-concrete composite shear connection', *Constr Build Mater*, vol. 425, p. 135982, Apr. 2024, doi: 10.1016/J.CONBUILDMAT.2024.135982.

[203] S. Shahnoori and M. Mohammadi, 'Construction for Health; Reversing the Impacts', *Buildings*, vol. 12, no. 8, p. 1133, Jul. 2022, doi: 10.3390/buildings12081133.

[204] B. Wallsten, 'The Urk World : Hibernating Infrastructures and the Quest for Urban Mining', Linkoping University, 2015. doi: 10.3384/diss.diva-122758.

[205] F. Heisel and D. E. Hebel, *Building Better - Less - Different: Circular Construction and Circular Economy*. Berlin, Boston: Birkhäuser, 2022. doi: doi:10.1515/9783035626353.

[206] M. Kuittinen, C. Zernicke, S. Slabik, and A. Hafner, 'How can carbon be stored in the built environment? A review of potential options', *Archit Sci Rev*, vol. 66, no. 2, pp. 91–107, Mar. 2023, doi: 10.1080/00038628.2021.1896471.

[207] A. Hafner and S. Schäfer, 'Environmental aspects of material efficiency versus carbon storage in timber buildings', *European Journal of Wood and Wood Products*, vol. 76, no. 3, pp. 1045–1059, May 2018, doi: 10.1007/s00107-017-1273-9.

[208] A. Sanna, M. Uibu, G. Caramanna, R. Kuusik, and M. M. Maroto-Valer, 'A review of mineral carbonation technologies to sequester CO2', *Chem. Soc. Rev.*, vol. 43, no. 23, pp. 8049–8080, 2014, doi: 10.1039/C4CS00035H.

[209] Z. Cao *et al.*, 'The sponge effect and carbon emission mitigation potentials of the global cement cycle', *Nat Commun*, vol. 11, no. 1, p. 3777, Jul. 2020, doi: 10.1038/s41467-020-17583-w.

[210] E. S. Slaughter, 'Design strategies to increase building flexibility', *Building Research & Information*, vol. 29, no. 3, pp. 208–217, May 2001, doi: 10.1080/09613210010027693.

[211] M. B. Hamida, T. Jylhä, H. Remøy, and V. Gruis, 'Circular building adaptability and its determinants – A literature review', *International Journal of Building Pathology and Adaptation*, vol. 41, no. 6, pp. 47–69, 2022, doi: 10.1108/IJBPA-11-2021-0150.

[212] G. Foster, 'Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts', *Resour Conserv Recycl*, vol. 152, Jan. 2020, doi: 10.1016/j.resconrec.2019.104507.

[213] D. O. Aytac, T. V. Arslan, and S. Durak, 'Adaptive Reuse as A Strategy Toward Urban Resilience', *European Journal of Sustainable Development*, vol. 5, no. 4, pp. 523–532, May 2016, doi: 10.14207/ejsd.2016.v5n4p523.

[214] G. Bertino, J. Kisser, J. Zeilinger, G. Langergraber, T. Fischer, and D. Österreicher, 'Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials', *Applied Sciences (Switzerland)*, vol. 11, no. 3, pp. 1–31, Feb. 2021, doi: 10.3390/app11030939.

[215] S. Brand, *How Buildings Learn: What Happens after They're Built*. New York: Penguin Books, 1994.

[216] World Business Council for Sustainable Development, 'The Building System Carbon Framework', 2020.

[217] O. O. Akinade *et al.*, 'Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills', *Waste Management*, vol. 60, pp. 3–13, Feb. 2017, doi: 10.1016/J.WASMAN.2016.08.017.

[218] B. Guy and N. Ciarimboli, 'DfD Design for Disassembly in the built environment: a guide to closed-loop design and building', 2005.

[219] M. Shalaby and K. Saitou, 'Design for Disassembly With High-Stiffness Heat-Reversible Locator-Snap Systems', *Journal of Mechanical Design*, vol. 130, no. 12, Dec. 2008, doi: 10.1115/1.2991134.

[220] K. Knoth, S. M. Fufa, and E. Seilskjær, 'Barriers, success factors, and perspectives for the reuse of construction products in Norway', *J Clean Prod*, vol. 337, p. 130494, Feb. 2022, doi: 10.1016/J.JCLEPRO.2022.130494.

[221] G. Bertino, J. Kisser, J. Zeilinger, G. Langergraber, T. Fischer, and D. Österreicher, 'Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials', *Applied Sciences (Switzerland)*, vol. 11, no. 3, pp. 1–31, Feb. 2021, doi: 10.3390/app11030939.

[222] T. Ros-Dosdá, I. Celades, L. Vilalta, P. Fullana-i-Palmer, and E. Monfort, 'Environmental comparison of indoor floor coverings', *Science of The Total Environment*, vol. 693, p. 133519, Nov. 2019, doi: 10.1016/J.SCITOTENV.2019.07.325.

[223] M. Smith, C. Gorse, C. Flood, L. Scott, and B. N. West, 'Retrofitting and refurbishment', in *Building Surveyor's Pocket Book*, Abingdon, Oxon; New York, NY: Routledge, 2021. |: Routledge, 2021, pp. 134–168. doi: 10.1201/9781315142647.

[224] I. E. Aigwi, A. Duberia, and A. N. Nwadike, 'Adaptive reuse of existing buildings as a sustainable tool for climate change mitigation within the built environment', *Sustainable Energy Technologies and Assessments*, vol. 56, p. 102945, Mar. 2023, doi: 10.1016/j.seta.2022.102945.

[225] L. M. Luscuere, 'Materials Passports: Optimising value recovery from materials', *Proceedings of the Institution of Civil Engineers - Waste and Resource Management*, vol. 170, no. 1, pp. 25–28, 2017, doi: 10.1680/jwarm.16.00016.

[226] Arup, 'The Circular Economy in the Built Environment', 2016.

[227] Luxembourg Institute of Science and Technology (LIST), 'Digital Deconstruction '. Accessed: Jan. 21, 2024. [Online]. Available: https://www.list.lu/en/informatics/project/digitaldeconstruction/

[228] The Ministry of Economy of Luxembourg, 'PCDS Product Circularity Data Sheet Luxembourg'. Accessed: Mar. 07, 2024. [Online]. Available: https://pcds.lu/

[229] A. X. Sanchez, K. D. Hampson, and S. Vaux, *Delivering Value with BIM: A whole-of-life approach*. 2016.

[230] R. Charef, 'The use of Building Information Modelling in the circular economy context: Several models and a new dimension of BIM (8D)', *Clean Eng Technol*, vol. 7, p. 100414, Apr. 2022, doi: 10.1016/j.clet.2022.100414.

[231] A. Aguiar, R. Vonk, and F. Kamp, 'BIM and Circular Design', *IOP Conf Ser Earth Environ Sci*, vol. 225, p. 012068, Feb. 2019, doi: 10.1088/1755-1315/225/1/012068.

[232] A. AKBARIEH, 'Information Modelling for Circular Transformation of Built Assets' End-Of-Life'.

[233] A. Akbarieh and S. Sarabi, 'Chapter 3 - Creating a universal semantic material bank: Integrating digital twins and semantic web technologies for circular urban mining', in *Digital Twins for Smart Metabolic Circular Cities*, S. E. Bibri, T. Yigitcanlar, and J. Huang, Eds., in Smart Cities. , Elsevier, 2025, pp. 49–72. doi: https://doi.org/10.1016/B978-0-443-33333-0.00003-X.

[234] R. Reed, A. Bilos, S. Wilkinson, and K.-W. Schulte, 'International Comparison of Sustainable Rating Tools', *Journal of Sustainable Real Estate*, vol. 1, no. 1, pp. 1–22, Jan. 2009, doi: 10.1080/10835547.2009.12091787.

[235] K. G. Jensen and H. Birgisdottir, *Guide to Sustainable Building Certifications*. 2018.

[236] T. Saunders, ' Discussion Document Comparing International Environmental Assessment Methods for Buildings', Glasgow, 2008.

[237] R. J. Cole, 'Transitioning from green to regenerative design', *Building Research and Information*, vol. 40, no. 1, pp. 39–53, Jan. 2012, doi: 10.1080/09613218.2011.610608.

[238] Government of Luxembourg, 'Loi du 23 décembre 2016 portant introduction d'une certification de la durabilité des logements et modifiant la loi modifiée du 25 février 1979 concernant l'aide au logement.', 2016, *Luxembourg*. Accessed: Nov. 21, 2023. [Online]. Available: http://data.legilux.public.lu/eli/etat/leg/loi/2016/12/23/n21/jo

[239] M. Liu, G. Zhu, and Y. Tian, 'The historical evolution and research trends of life cycle assessment', *Green Carbon*, Sep. 2024, doi: 10.1016/j.greenca.2024.08.003.

[240] International Organization for Standardization, 'ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines', 2006. Accessed: Oct. 11, 2024. [Online]. Available: https://www.iso.org/standard/38498.html

[241] International Organization for Standardization, 'ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework', 2006. Accessed: Oct. 11, 2024. [Online]. Available: https://www.iso.org/standard/37456.html

[242] International Organization for Standardization, 'ISO 59004:2024 Circular economy — Vocabulary, principles and guidance for implementation', 2024. Accessed: Oct. 01, 2024. [Online]. Available: https://www.iso.org/standard/80648.html

[243] The International Living Future Institute, 'The Living Building Challenge', 2024.

[244] A. Dada, 'Living Systems: Planting Liberation', 2024. Accessed: Sep. 04, 2024. [Online]. Available: https://slowfactory.earth/courses/living-systems-planting-liberation/

[245] A. Gattupalli, 'What is Regenerative Architecture? Limits of Sustainable Design, System Thinking Approach and the Future', *Arch Daily*, Mar. 05, 2023.

[246] D. Waldron, A. Cayuela, and D. Miller, 'Regenerative Neighbourhoods – scaling up from net positive buildings', in *Canada Green Building Council National Conference (SB13)*, 2013.

[247] Global Footprint Network, 'Earth Overshoot Day'. Accessed: Jun. 07, 2024. [Online]. Available: https://overshoot.footprintnetwork.org/newsroom/press-release-june-2024-english/

[248] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 'Summary for policymakers of the global assessment report on

biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services', 2019. Accessed: Jul. 01, 2024. [Online]. Available: https://ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf

[249] J. Robinson and R. J. Cole, 'Theoretical underpinnings of regenerative sustainability', *Building Research and Information*, vol. 43, no. 2, pp. 133–143, Mar. 2015, doi: 10.1080/09613218.2014.979082.

[250] O. N. Oyefusi, W. I. Enegbuma, A. Brown, and O. I. Olanrewaju, 'Development of a novel performance evaluation framework for implementing regenerative practices in construction', *Environ Impact Assess Rev*, vol. 107, Jul. 2024, doi: 10.1016/j.eiar.2024.107549.

[251] B. Reed, 'Shifting from "sustainability" to regeneration', *Building Research & Information*, vol. 35, no. 6, pp. 674–680, Nov. 2007, doi: 10.1080/09613210701475753.

[252] C. du Plessis, 'Towards a regenerative paradigm for the built environment', *Building Research & Information*, vol. 40, no. 1, pp. 7–22, Jan. 2012, doi: 10.1080/09613218.2012.628548.

[253] R. J. Cole, 'Regenerative design and development: current theory and practice', *Building Research & Information*, vol. 40, no. 1, pp. 1–6, Jan. 2012, doi: 10.1080/09613218.2012.617516.

[254] S. Attia, 'Towards regenerative and positive impact architecture: A comparison of two net zero energy buildings', *Sustain Cities Soc*, vol. 26, pp. 393–406, Oct. 2016, doi: 10.1016/J.SCS.2016.04.017.

[255] P. Hernandez and P. Kenny, 'From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)', *Energy Build*, vol. 42, no. 6, pp. 815–821, Jun. 2010, doi: 10.1016/j.enbuild.2009.12.001.

[256] S. J. Buckton *et al.*, 'The Regenerative Lens: A conceptual framework for regenerative social-ecological systems', *One Earth*, vol. 6, no. 7, pp. 824–842, Jul. 2023, doi: 10.1016/j.oneear.2023.06.006.

[257] M. Sparrevik, L. de Boer, O. Michelsen, C. Skaar, H. Knudson, and A. M. Fet, 'Circular economy in the construction sector: advancing environmental performance through systemic and holistic thinking', *Environ Syst Decis*, vol. 41, no. 3, pp. 392–400, Sep. 2021, doi: 10.1007/s10669-021-09803-5.

[258] H. Sala Benites, P. Osmond, and D. Prasad, 'A neighbourhood-scale conceptual model towards regenerative circularity for the built environment', *Sustainable Development*, vol. 31, no. 3, pp. 1748–1767, Jun. 2023, doi: 10.1002/sd.2481.

[259] P. Centobelli, R. Cerchione, D. Chiaroni, P. Del Vecchio, and A. Urbinati, 'Designing business models in circular economy: A systematic literature review and research agenda', *Bus Strategy Environ*, vol. 29, no. 4, pp. 1734–1749, May 2020, doi: 10.1002/bse.2466.

[260] N. M. P. Bocken, I. de Pauw, C. Bakker, and B. van der Grinten, 'Product design and business model strategies for a circular economy', *Journal of Industrial and Production Engineering*, vol. 33, no. 5, pp. 308–320, Jul. 2016, doi: 10.1080/21681015.2016.1172124.

[261] J. Kirchherr, N.-H. N. Yang, F. Schulze-Spüntrup, M. J. Heerink, and K. Hartley, 'Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions', *Resour Conserv Recycl*, vol. 194, p. 107001, Jul. 2023, doi: 10.1016/j.resconrec.2023.107001.

[262] I. Papamichael *et al.*, 'Thriving in circularity: Vitality of business models development in circular (bio)economy', *Curr Opin Green Sustain Chem*, vol. 48, p. 100934, Aug. 2024, doi: 10.1016/j.cogsc.2024.100934.

[263] 'Oxford English Dictionary', Policy, (n.). Accessed: Feb. 23, 2024. [Online]. Available: https://doi.org/10.1093/OED/1186284385

[264] D. Harper, ‘Online Etymology Dictionary’. Accessed: Feb. 23, 2024. [Online]. Available: https://www.etymonline.com/word/policy

[265] B. Jordan, ‘Policies for Sustainability’, in *Immigration, Social Cohesion and Political Reaction*, Cham: Springer International Publishing, 2021, pp. 69–77. doi: 10.1007/978-3-030-52708-2_6.

[266] H. Nykamp, ‘Policy Mix for a Transition to Sustainability: Green Buildings in Norway’, *Sustainability*, vol. 12, no. 2, p. 446, Jan. 2020, doi: 10.3390/su12020446.

[267] M. Calisto Friant, W. J. V. Vermeulen, and R. Salomone, ‘Analysing European Union circular economy policies: words versus actions’, *Sustain Prod Consum*, vol. 27, pp. 337–353, Jul. 2021, doi: 10.1016/j.spc.2020.11.001.

[268] C. Knill, Y. Steinebach, and X. Fernández-i-Marín, ‘Hypocrisy as a crisis response? Assessing changes in talk, decisions, and actions of the European Commission in EU environmental policy’, *Public Adm*, vol. 98, no. 2, pp. 363–377, Jun. 2020, doi: 10.1111/padm.12542.

[269] O. Fitch-Roy, D. Benson, and D. Monciardini, ‘Going around in circles? Conceptual recycling, patching and policy layering in the EU circular economy package’, *Env Polit*, vol. 29, no. 6, pp. 983–1003, Sep. 2020, doi: 10.1080/09644016.2019.1673996.

[270] K. Hobson and N. Lynch, ‘Diversifying and de-growing the circular economy: Radical social transformation in a resource-scarce world’, *Futures*, vol. 82, pp. 15–25, Sep. 2016, doi: 10.1016/j.futures.2016.05.012.

[271] European Commission, ‘EU Laws’, Types of EU law. Accessed: Feb. 23, 2024. [Online]. Available: https://commission.europa.eu/law/law-making-process/types-eu-law_en#legislative-vs-non-legislative

[272] European Commission, ‘Closing the loop - An EU action plan for the Circular Economy’, Brussels, 2015.

[273] L. Milios, 'Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix', May 01, 2018, *Springer Tokyo*. doi: 10.1007/s11625-017-0502-9.

[274] European Commission, 'The European Green Deal'. Accessed: Jan. 03, 2025. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[275] European Commission, 'The Circular Economy Action Plan'. Accessed: Jan. 03, 2025. [Online]. Available: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[276] European Commission, 'Strategy for a Sustainable Built Environment'. Accessed: Feb. 20, 2025. [Online]. Available: https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-strategy-for-a-sustainable-built-environment

[277] European Commission, 'Level(s)'. Accessed: Oct. 10, 2024. [Online]. Available: https://environment.ec.europa.eu/topics/circular-economy/levels_en

[278] European Commission, 'Waste Framework Directive'. Accessed: Jul. 13, 2024. [Online]. Available: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en#end-of-waste-criteria

[279] Institute for Prospective Technological Studies (Joint Research Centre) *et al.*, 'End-of-waste criteria', 2009. Accessed: Aug. 13, 2024. [Online]. Available: https://data.europa.eu/doi/10.2791/28650

[280] European Commission, 'Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020', 2024.

[281] European Commission, 'Material system analysis (MSA)'. Accessed: Aug. 05, 2024. [Online]. Available: https://single-market-

economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/material-system-analysis-msa_en

[282] U. Eynard *et al.*, 'Study on the EU's list of Critical Raw Materials: Non-Critical Raw Materials Factsheets', 2020. doi: 10.2873/867993.

[283] European Commission, 'Ecodesign for Sustainable Products Regulation'. Accessed: Aug. 20, 2024. [Online]. Available: https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en

[284] European Commission, 'Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC', 2024. Accessed: Aug. 20, 2024. [Online]. Available: http://data.europa.eu/eli/reg/2024/1781/oj

[285] S. Hollanders, 'Mineralogical study of the pozzolanic properties of calcined clays', KU Leuven, Leuven, 2017.

[286] B. B. Sabir, S. Wild, and J. Bai, 'Metakaolin and calcined clays as pozzolans for concrete: a review', *Cem Concr Compos*, pp. 441–454, 2001, [Online]. Available: www.elsevier.com/locate/cemconcomp

[287] S. Chakurkar (Anawkar) and K. G. Guptha, 'Optimization of cement quantity through the engineering of particle size distribution – a sustainable approach', *Results in Materials*, vol. 19, p. 100408, Sep. 2023, doi: 10.1016/J.RINMA.2023.100408.

[288] European Committee for Standardization, 'EN 196-6:2018 - Methods of testing cement - Part 6: Determination of fineness', 2018.

[289] V. K. Singh, 'Classification of pozzolana and production of pozzolanic cements', in *The Science and Technology of Cement and Other Hydraulic*

Binders, Elsevier, 2023, pp. 653–694. doi: 10.1016/B978-0-323-95080-0.00018-2.

[290] J. Millward-Hopkins, J. K. Steinberger, N. D. Rao, and Y. Oswald, 'Providing decent living with minimum energy: A global scenario', *Global Environmental Change*, vol. 65, p. 102168, Nov. 2020, doi: 10.1016/J.GLOENVCHA.2020.102168.

[291] M. Schneider, 'The cement industry on the way to a low-carbon future', *Cem Concr Res*, vol. 124, p. 105792, Oct. 2019, doi: 10.1016/J.CEMCONRES.2019.105792.

[292] A. Shvarzman, K. Kovler, G. S. Grader, and G. E. Shter, 'The effect of dehydroxylation/amorphization degree on pozzolanic activity of kaolinite', *Cem Concr Res*, vol. 33, no. 3, pp. 405–416, Mar. 2003, doi: 10.1016/S0008-8846(02)00975-4.

[293] M. Amar, M. Benzerzour, N. E. Abriak, and Y. Mamindy-Pajany, 'Study of the pozzolanic activity of a dredged sediment from Dunkirk harbour', *Powder Technol*, vol. 320, pp. 748–764, Oct. 2017, doi: 10.1016/j.powtec.2017.07.055.

[294] R. Berenguer *et al.*, 'Cement-based materials: Pozzolanic activities of mineral additions are compromised by the presence of reactive oxides', *Journal of Building Engineering*, vol. 41, Sep. 2021, doi: 10.1016/j.jobe.2021.102358.

[295] V. Nežerka, Z. Slížková, P. Tesárek, T. Plachý, D. Frankeová, and V. Petráňová, 'Comprehensive study on mechanical properties of lime-based pastes with additions of metakaolin and brick dust', *Cem Concr Res*, vol. 64, pp. 17–29, 2014, doi: 10.1016/j.cemconres.2014.06.006.

[296] E. R. Grist, K. A. Paine, A. Heath, J. Norman, and H. Pinder, 'Compressive strength development of binary and ternary lime-pozzolan mortars', *Mater Des*, vol. 52, pp. 514–523, 2013, doi: 10.1016/j.matdes.2013.05.006.

[297] J. M. Inocente, F. Elyseu, L. J. Jaramillo Nieves, J. Jiusti, M. Cargnin, and M. Peterson, 'Production and characterization of high-reactivity metakaolins

calcined in flash reactor', *Appl Clay Sci*, vol. 213, Nov. 2021, doi: 10.1016/j.clay.2021.106247.

[298] Y. Wang, Z. Shui, Y. Huang, T. Sun, R. Yu, and G. Wang, 'Improving the pozzolanic activity of metakaolin by urea intercalation technique', *Constr Build Mater*, vol. 172, pp. 19–28, May 2018, doi: 10.1016/j.conbuildmat.2018.03.189.

[299] V. M. de Oliveira, F. de Souza, R. T. da Cruz, L. G. Py, A. P. Kirchheim, and S. R. Bragança, 'Valorization of non-beneficiated clays as supplementary cementitious materials in the production of cement-based mortar', *Journal of Building Engineering*, vol. 42, Oct. 2021, doi: 10.1016/j.jobe.2021.102474.

[300] Y. Liu, S. Lei, M. Lin, Y. Li, Z. Ye, and Y. Fan, 'Assessment of pozzolanic activity of calcined coal-series kaolin', *Appl Clay Sci*, vol. 143, pp. 159–167, Jul. 2017, doi: 10.1016/j.clay.2017.03.038.

[301] E. Vejmelková *et al.*, 'Effect of calcined Czech claystone on the properties of high performance concrete: Microstructure, strength and durability', *Constr Build Mater*, vol. 168, pp. 966–974, Apr. 2018, doi: 10.1016/j.conbuildmat.2018.02.204.

[302] ASTM International, 'C618 – 15 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete 1'. doi: 10.1520/C0618-15.

[303] V. T. Nguyen, S. Y. Lee, S.-Y. Chung, J.-H. Moon, and D. J. Kim, 'Effects of cement particle distribution on the hydration process of cement paste in three-dimensional computer simulation', *Constr Build Mater*, vol. 311, p. 125322, Dec. 2021, doi: 10.1016/j.conbuildmat.2021.125322.

[304] B. Samet, T. Mnif, and M. Chaabouni, 'Use of a kaolinitic clay as a pozzolanic material for cements: Formulation of blended cement', *Cem Concr Compos*, vol. 29, no. 10, pp. 741–749, Nov. 2007, doi: 10.1016/J.CEMCONCOMP.2007.04.012.

[305] S. Daly, A. Mcgowan, and P. Papalambros, 'Using qualitative research methods on engineering design research', in *International Conference on Engineering Design*, Seoul, Aug. 2013.

[306] J. Carlos Gonçalves dos Reis and M. Amorim, 'Breaking Barriers with Qualitative Multi-method Research for Engineering Studies: Pros, Cons and Issues'. [Online]. Available: https://www.researchgate.net/publication/316171688

[307] J. W. Creswell, *Qualitative Inquiry & Research Design*, 3rd ed. Sage, 2013.

[308] J. P. Murphy, *Pragmatism: From Peirce To Davidson*. Avalon Publishing , 1990.

[309] M. Marsonet, 'Pragmatism and Science', *Academicus : International Scientific Journal*, vol. 8, pp. 101–109, 2013.

[310] J. Ravetz, *Scientific knowledge and its social problems*. New York: Oxford University Press, 1971.

[311] S. Brinkmann, *Qualitative interviewing : conversational knowledge through research interviews*. New York, NY: Oxford University Press, 2022.

[312] Tom. Wengraf, *Qualitative research interviewing : biographic narrative and semi-structured methods /*. London: SAGE, 2001.

[313] S. Mann, *The research interview: Reflective practice and reflexivity in research processes*. 2016. doi: 10.1057/9781137353368.

[314] B. DiCicco-Bloom and B. F. Crabtree, 'The qualitative research interview', Apr. 2006. doi: 10.1111/j.1365-2929.2006.02418.x.

[315] H. Kallio, A.-M. Pietilä, M. Johnson, and M. Kangasniemi, 'Systematic methodological review: developing a framework for a qualitative semi-structured interview guide', *J Adv Nurs*, vol. 72, no. 12, pp. 2954–2965, 2016, doi: https://doi.org/10.1111/jan.13031.

[316] S. Rahimi and M. khatooni, 'Saturation in qualitative research: An evolutionary concept analysis', *Int J Nurs Stud Adv*, vol. 6, p. 100174, Jun. 2024, doi: 10.1016/j.ijnsa.2024.100174.

[317] M. Hennink and B. N. Kaiser, 'Sample sizes for saturation in qualitative research: A systematic review of empirical tests', *Soc Sci Med*, vol. 292, Jan. 2022, doi: 10.1016/j.socscimed.2021.114523.

[318] C. T. Williams-Mcbean, 'The value of a qualitative pilot study in a multi-phase mixed methods research', *Qualitative Report*, vol. 24, no. 5, pp. 1055–1064, May 2019, doi: 10.46743/2160-3715/2019.3833.

[319] K. T. Aung, R. A. Razak, and N. N. M. Nazry, 'Establishing Validity And Reliability of Semi-Structured Interview Questionnaire in Developing Risk Communication Module: A Pilot Study', *Edunesia : Jurnal Ilmiah Pendidikan*, vol. 2, no. 3, pp. 600–606, Jun. 2021, doi: 10.51276/edu.v2i3.177.

[320] J. W. Creswell and J. D. Creswell, *Research design: qualitative*, *quantitative*, *and mixed methods approaches*, 5th ed. Los Angeles: SAGE, 2018.

[321] H. Noble and G. Mitchell, 'What is grounded theory?', *Evidence Based Nursing*, vol. 19, no. 2, pp. 34–35, Apr. 2016, doi: 10.1136/eb-2016-102306.

[322] A. Bryant, 'The Grounded Theory Method', in *The Oxford Handbook of Qualitative Research*, P. Leavy, Ed., Oxford University Press, 2014, pp. 115–136. doi: 10.1093/oxfordhb/9780199811755.013.016.

[323] M. M. Hennink, B. N. Kaiser, and V. C. Marconi, 'Code Saturation Versus Meaning Saturation', *Qual Health Res*, vol. 27, no. 4, pp. 591–608, Mar. 2017, doi: 10.1177/1049732316665344.

[324] D. Ribeiro, *Lugar de Fala*. Editora Jandaira, 2020.

[325] A. Youngblood Jackson and L. Mazzei, *Thinking with Theory in Qualitative Research*. Routledge, 2011. doi: 10.4324/9780203148037.

[326] C. D. D. Rupprecht *et al.*, 'Multispecies sustainability', *Global Sustainability*, vol. 3, p. e34, Dec. 2020, doi: 10.1017/sus.2020.28.

[327] R. Bhaskar, 'On the Ontological Status of Ideas', *J Theory Soc Behav*, vol. 27, no. 2–3, pp. 139–147, Jun. 1997, doi: 10.1111/1468-5914.00031.

[328] J. Berger, *Ways of Seeing*. Penguin Books, 1972.

[329] O. E. Ogunmakinde, W. Sher, and T. Egbelakin, ‘Circular economy pillars: a semi-systematic review’, *Clean Technol Environ Policy*, vol. 23, no. 3, pp. 899–914, Apr. 2021, doi: 10.1007/s10098-020-02012-9.

[330] Ellen MacArthur Foundation, ‘Building Prosperity: Unlocking the potential of a nature-positive, circular economy for Europe’, 2024.

[331] M. Geissdoerfer, P. Savaget, N. M. P. Bocken, and E. J. Hultink, ‘The Circular Economy – A new sustainability paradigm?’, *J Clean Prod*, vol. 143, pp. 757–768, Feb. 2017, doi: 10.1016/J.JCLEPRO.2016.12.048.

[332] L. Milios, ‘Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix’, May 01, 2018, *Springer Tokyo*. doi: 10.1007/s11625-017-0502-9.

[333] P. Brown, C. Von Daniels, N. M. P. Bocken, and A. R. Balkenende, ‘A process model for collaboration in circular oriented innovation’, *J Clean Prod*, vol. 286, p. 125499, Mar. 2021, doi: 10.1016/J.JCLEPRO.2020.125499.

[334] M. Haines-Gadd, C. Bakker, and F. Charnley, ‘8 Circular design in practice: eight levers for change’, in *Handbook of the Circular Economy*, De Gruyter, 2023, pp. 97–124. doi: 10.1515/9783110723373-011.

[335] P. Ghisellini, C. Cialani, and S. Ulgiati, ‘A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems’, *J Clean Prod*, vol. 114, pp. 11–32, Feb. 2016, doi: 10.1016/J.JCLEPRO.2015.09.007.

[336] P. Schosseler, J. Schroeder, K. Hansen, and D. Mulhall, ‘Null Offall Lëtzebuerg’, 2020.

[337] Observatoire de la Politique Climatique, ‘OPC statement on the draft PNEC update ref: OPC/(2023)OPI02 ’, 2023.

[338] B. Preller, ‘Luxembourg: A policy-led approach caught between green growth and affordable housing’, in *Urban Book Series*, no. 9783319777085, Springer, 2018, pp. 159–188. doi: 10.1007/978-3-319-77709-2_8.

[339] Fritjof Capra, *The Web of Life*, 1st ed. New York: Anchor Books, 1997.

[340] P. Hild, 'The Circular Economy and Circular Building Practices in Luxembourg', *Circular Economy and Sustainability*, vol. 3, no. 4, pp. 1963–1988, Dec. 2023, doi: 10.1007/s43615-023-00256-3.

[341] S. Jasanoff, 'Technologies of Humility: Citizen Participation in Governing Science', *Minerva*, vol. 41, no. 3, pp. 223–244, 2003, [Online]. Available: http://www.jstor.org/stable/41821248

[342] European Commission, 'European Governance: A White Paper', Brussels, Jul. 2001. Accessed: Jan. 21, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52001DC0428

[343] E. Manzini, *Design*, *When Everybody Designs*. The MIT Press, 2015.

[344] W. R. Stahel, *The Performance Economy*. London: Palgrave Macmillan UK, 2010. doi: 10.1057/9780230288843.

[345] Y. Cai, J. Ma, and Q. Chen, 'Higher education in innovation ecosystems', Jun. 01, 2020, *MDPI*. doi: 10.3390/su12114376.

[346] M. Saunders, P. Lewis, and A. Thornhill, 'Understanding research philosophies and approaches', *Research Methods for Business Students*, vol. 4, pp. 106–135, Oct. 2009.

Part VI | Annexes

10 Annexes

10.1 Annex 1: Interview questionnaire.

Introduction

Objective: to set the scene and learn what defines CE policy in relation to C emissions and sequestration, also to get a bit into the philosophical discussion behind and the core concepts in the interviewee's stance.

Would you please introduce yourself and state your name, organization, and role in it?

What interests you in this field and encourages you to take part in this interview?

1.1 Definiton. How do you define circularity in the built environment, and what are its key principles and benefits in your experience? I would invite you here to think in absolute and relative terms.

1.2 Standard. Thinking of circular building environments – what would be your gold standard? How far are we away from that? i.e. Where do we stand in Luxembourg (also Europe) in respect to this now compared to 10 years ago? – *note to explore tension between knowledge and practice.*

1.3 Goals. When we think of circularity in the built environment we naturally think of the future of the industry, what are in your view the most important goals to achieve for the sector and its industry? Thinking in terms of tensions, threats, barriers, what is missing to get there?

1.4 Could you think of any disruptive events that can affect both positively and negatively i.e. accelerate or decelerate the progress?

Stakeholders block

Objective: to understand who are the stakeholders that influence and are influenced by the CE concepts and applications in the construction sector, and how does the stakeholder landscape look like.

2.1 Who are the primary stakeholders involved in circularity (circular economy) in the construction sector, and what are their roles and responsibilities? How do they connect and interact with one another in terms of relationship quality and dependency *i.e. thinking of value creation*?

2.2 In what ways, in your experience, can the different stakeholders we mentioned collaborate effectively to promote circularity in the built environment? Would you share any cases of successful or failed cooperation that you know of?

2.4 How do the interests and objectives of different stakeholders involved in the construction sector intersect or conflict with circular economy policy and concepts?

2.5 What are the key challenges in engaging and motivating stakeholders to support circular economy applications in the construction sector, and how can these challenges be overcome?

2.8 Do you see the construction sector becoming more open and inclusive of all of its stakeholders or do you think it is a hard equation to solve?

Policy block

Objective: to map the national and municipal policies on CE and how they promote circularity in the built environment, what challenges they face and how can these be overcome. Which policies hinder and which ones advance?

3.1 We know that effective climate action is enabled by political commitment and well-aligned institutional frameworks[5] what policies and regulations currently exist to promote circularity in the built environment, and how effective have they been in achieving their goals?

3.2 We spoke about goals to achieve. Do you think the set of goals we have now can structurally contribute towards a systemic transformation and if so in what ways? If not, what is missing?

3.4 According to a report[6] published by the Ellen Macarthur foundation, the first step to get CE principles into practice is to identify policy changes. Are there any existing policies that are hindering the implementation of CE concepts? What are some of the key barriers to

[5] IPCC AR6 Summary for Policymakers p. 36 section C.6
[6] Report: First steps towards a circular built environment – ARUP and Ellen Macarthur Foundation

implementing circularity in the built environment, and how can public policy help overcome these barriers? *(Which policies empower and which ones constrain?)*

3.6 Measuring What are some of the key metrics that in your view should be used to measure the success of public policies promoting circularity in the built environment? And how important is measuring as a step towards achieving more?

3.9 Could you share some of the most promising examples of circular building practices that you have seen (doesn't matter at which level from materials to buildings to cities), and how can public policy help in scaling these practices up? Are all the stakeholders on the same page, i.e. do they all know what is happening around in terms of innovative practices in your opinion?

Materials block

Objective: A continuation to the initial research to probe into the reasons as to why SCMs are still not widely used in all their array from demolition waste to high quality slag, on top of the previous blocks.

4.1 It is known that the concept of geopolymers and supplementary cementitious materials lowering binder to clinker ratio in concrete, or even biobased materials is not a new invention, yet very promising. Why have we not advanced in a way towards using more and more of those concepts as commercial construction materials in your opinion?

4.2 What are the conceptual and technical challenges from the point of view of material science and how does it impact the choice of design engineers and construction companies?

4.3 Thinking beyond (but not excluding) technical terms, what the barriers to the adoption and spread of new material technologies? Is it a systemic issue in your point of view or more of a technology that simply doesn't fulfill the needs of the market?

Future outlook block

Objective: As we envision a future built environment established on the basis of an urban regenerative and abundant learning system, it is crucial to understand how do the people who are shaping the sector see it in the future.

5.1 We read a lot about the barriers to circular economy and the critiques building on unclear implementability, the uncertainties on system boundaries and the difficulties to measure and assess CE practices, what do you think about this and how does it affect the advance and improvement of CE in the built environment?

5.2 How does the built environment of the future differ from the one we have today? How does it look like on different layers? In other words what does the circular city of the future look like?

5.3 At the heart of an inclusive ecological transition lies a circular vision and strategy with clear goals and targets, ideally carried out in a participatory manner, how do you see this and how does it catalyze the process? Are there any steps that you consider essential?

Conclusion block

6.1 Would you like to add any remarks or ideas of particular importance that we have not covered during the talk?

6.2 Let's say we had a crystal ball and you could ask one question, of course related to our field, what would it be? / Would there be a question that I did not ask that you think is important?

10.2 Annex 2: Coding system used in interview analysis.

Code	Description of content
Challenge for circularity	Addresses the main obstacles, including societal, technical, economic, and regulatory challenges, in transitioning to a circular economy in the built environment.
Change for circularity	Examines the systemic changes required across industries and sectors to facilitate the shift toward a circular economy.
Circularity definition	Provides a comprehensive definition of circularity, particularly in the context of the built environment, emphasizing the different views of the participants that affect their stances on circularity and sustainability.
Cost of circularity	Highlight the financial implications of adopting circular strategies, or the effects that arise from finance questions.
Education for circularity	Highlights the connection of education of professionals and the public with advancement of circular economy principles and practices in the construction sector.
Examples of circular projects	Provides the examples of real-world construction projects that have successfully implemented circular economy principles referred to by the interviewed experts.
Future of the BE	Explores predictions and strategies for how the built environment can evolve in the future.
Good practices in circularity	Highlights best practices and proven strategies for achieving circularity in construction projects.
Human agency	Explores the role of individual stakeholders in driving or hindering circularity initiatives.
Material technology	Discusses the question of material science innovations that support circularity, the challenges, and the nature of technological transitions.

Measuring circularity	Strings that are related to methods of evaluating the circularity of materials, processes, policy, and systems in the built environment and its importance.
New business models	Examines business models that support circularity.
Opportunity for circularity	Highlights the potential opportunities that appear to be able to push for circularity in the built environment.
Personal drive for circularity	Discusses how individual motivations, ethics, and beliefs contribute to the pursuit of circularity in the built environment.
Policy element	Discusses key policy components necessary to support the adoption of circularity in construction and urban planning. Policies were identified by a highlight that does not feature in the code list.
Policy hinders	Identifies current policies or related elements that may obstruct the transition to a circular economy in the built environment. This code also contains the mapping of certain blind spots identified by the interviewees.
Reflections	Offers critical insights and reflections from the participants with a wider view and often a question-without-an-answer type of interjection that do not really fit into a proper category.
Regenerative circularity	Focuses on circularity approaches that see nature not as a resource but recognize interdependence of humans and the surrounding environment pushing towards a net-positive view that regenerates ecosystems and resources.
Role of citizens	Explores how public participation and non-expert citizens influence the success of circular initiatives in the built environment.
Social aspect of circularity	Looks at the social aspects and implications of circularity.

Stakeholder connections	Describes the relationships between various stakeholders in implementing circular strategies in construction projects.
Stakeholders	Provides information related to stakeholders involved in circular economy projects, but that are non-relational.
Stakeholders identification	A tag that identifies and counts stakeholders and classifies them into three categories: core, important, and interesting.
Strength for circularity	Identifies the strengths and advantages of implementing circularity, or that can help implement it.
Threat for circularity	Maps potential risks or challenges that could undermine circular economy efforts, such as lack of resources or resistance to change.
Urgency	Identifies the pressing need to adopt circular practices in response to sustainability challenges.

10.3 Annex 3: List of relevant complementary policy documents or initiatives not present in the interview data.

A. **Baucheck in the context of the Pacte Climat** *(Klima Agence)*

The BauCheck[7] launched in 2024 (after the end of the data collection phase) and therefore naturally not mentioned in the interviews, is a tool developed by Klima Agence as part of the Pacte Climat to assist municipalities in making decisions in line with sustainable and circular construction and renovation decisions for buildings in the format of a framework. The document is structured into three chapters covering 14 themes and 45 objectives related to circular economy, climate adaptation, air quality, and biodiversity.

From the viewpoint of the ontological classification developed in the data analysis, the document pushes forward towards a holistic setting with the inclusion of biodiversity and healthy environment in its themes, as well as a whole life cycle consideration that is not only based on carbon emissions but on resource use intensity as well. One more aspect is the focus on the inverted resource pyramid first introduced by the Circular Economy Strategy of Luxembourg mentioned in section 6.1.1.3.1.5. Certain concepts such as building less, and building smarter, and steering away from just minimizing waste are all elements of a pragmatic and connected vision of circular economy, and it all translates into a tool that summarizes the framework with a complete excel file made available by the Klima Agence in which a project can be evaluated at its different phases, especially giving an extra importance to the design phase in which changes are still impactful and do not cost a lot to execute or introduce.

This policy element complements the other policies listed and discussed in the data analyses, however it is still directed towards the communes and could be extended towards the general construction sector.

[7] Guide to the implementation of BauCheck www.pacteclimat.lu

B. **Guide éco-urbanisme**[8] *(Ministère de l'Energie et de l'Aménagement du Territoire)*

The Guide is the fruit of a consultancy work with the objective of creating positive impacts in the urban environment and is organized under three tabs: the human, the resource, and the methods sections, each of which studies multiple themes related to transition towards a more sustainable urban future. The three tabs make its content and extent holistic and systemic at the same time since it addresses issues beyond material efficiency and goes one step further than all other policy elements to specifically address methodology in two themes: co-creation and participation, which are elements that were mentioned in the interview data by some of the participants as important factors to be able to implement circular strategies.

The guide is based on the value hill concept of circular economy (please see literature chapter), that takes into consideration the value of materials in a closed loop system along a whole life cycle. It is applied in a way that it adapts to a variety of urban elements including but not limited to buildings and building materials, as a way of keeping the highest social, economic, and ecological value alike.

Strategies 9 to 11 of the document , are the ones related to building and building materials, but there are no direct mentions of SCM that can relate to an analysis of the strategies that might be related to the use of materials studied in CO2REDRES except for the action on limiting waste that can therefore be applied as a concept of integrating waste or secondary materials into an existing product such is the case for concrete with additions.

A strong point of the guide is its wide and systemic vision of circularity, that is not consistently present in other documents, and the fact that it is not widely referenced in actual policy documents.

[8] Guide Eco-urbanisme, *Ministère de l'Energie et de l'Aménagement du Territoire*, *2021*.

C. The "Livre blanc: l'économie sociale et solidaire comme levier pour l'économie circulaire en Grande Région" (MTEESS, 2021)

The 2021 White Paper on Social and Solidarity Economy as a Lever for the Circular Economy in the Greater Region was commissioned by Luxembourg's Ministry of Labour, Employment and the Social and Solidarity Economy (SSE). Covering Luxembourg and the greater region (just like project CO2REDRES), it provides a 7 month analysis of the synergies between SSE and the CE based on interview data. The report highlights existing initiatives, cross-border cooperation potential and proposes actions to foster a resilient, resource efficient economy. It emphasizes SSE's ability to drive CE through social impact, job creation and innovative reuse models, among other actions and aligns with a holistic approach of circularity embedding elements of social connection and pragmatism not very present in other initiatives.

The White Paper identifies the construction sector as a priority for circular economy strategies because of its high material consumption and waste generation as it has been discussed in the thesis as well. It recommends structuring cross border ecosystems around deconstruction, recycling and reuse of building materials. Policy measures proposed include the creation of a "right to experiment" framework (sandbox) to test innovative circular building practices; pushing concepts of co-creation and testing solutions, the development of interoperable digital tools and material passports to track resources; and the strengthening of networks and clusters that connect SSE actors with construction companies. It also calls for financial instruments dedicated to circular construction initiatives and for the establishment of shared platforms for salvaging and redistributing construction components across the Greater Region.

Examples include: Neomaterial Luxembourg, which develops reuse chains for deconstructed materials, and Cycle-Up Lorraine, a digital marketplace linking construction companies with reclaimed building products. Both initiatives show how SSE actors can reduce demolition waste, extend material life cycles and accelerate the shift from linear to circular building practices, going beyond just material technicalities into real world experimentation. Therefore, the pragmatic aspect shows strongly.