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Experimental Investigation of Thermal Volumetric Changes in Clays: Unveiling Hidden Controls

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Abstract:	This endeavour investigates the thermally induced volumetric behaviour of fine-grained soils, specifically focusing on the effects of over-consolidation ratio (OCR), plasticity, and stress history. A custom-designed temperature-controlled oedometer cell was used to conduct drained heating and heating-cooling cycle tests on silty clays from Budapest, Hungary. The results reveal that normally consolidated samples exhibit plastic contraction upon heating, while over-consolidated samples show varying responses influenced by their recent stress history and plasticity index. Overconsolidated soil samples with a recent stress history of loading (reloading) predominantly contracted rather than the traditionally expected initial expansion, highlighting the importance of recent stress paths. Plasticity significantly impacts volumetric strain, with higher-plasticity clays exhibiting more pronounced contractions during heating and greater cumulative plastic strain over thermal cycles. The study concludes that a combination of OCR, plasticity, and stress history collectively determine the thermal volume response of fine-grained soils, with implications for the design of thermally robust geo-energy infrastructures.

Manuscript File

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Dear Editors

February 3, 2025

I am pleased to submit our manuscript, entitled **"Experimental Investigation of Thermal Volumetric Changes in Clays: Unveiling Hidden Controls,"** for consideration in *Engineering Geology*.

Given the journal's focus on geohazards, site characterization, tunnel engineering, and other related domains, we believe our work offers valuable insights into the thermal-mechanical processes of clayey soils. Our research addresses both engineering geology and geotechnical engineering concerns, showing how key parameters—over-consolidation ratio (OCR), plasticity index (PI), and stress history—dictate the behavior of fine-grained soils under thermo-mechanical loads. We present an experimental program especially relevant to:

- **Geohazards and Risk Assessment:** Understanding how clayey layers respond to heat is essential in regions where tunnels, underground storage facilities, or geothermal systems may face elevated temperatures, affecting both slope stability and site characterization.
- **Site Characterization and Thermo-Hydro-Mechanical (THM) Behavior:** Our temperature-controlled oedometer tests provide new data on how stress history influences volumetric changes, linking to THM properties crucial in landslide assessments and rock-hazard evaluations.
- **Time-Dependent Processes in Clays:** We show how repeated heating–cooling cycles can lead to either progressive or stabilized strains, relevant to the long-term performance of geological barriers and soils exposed to fluctuating subsurface temperatures.

We have modified our manuscript to align with the standards of *Engineering Geology*, including an expanded geological background, their mineralogy, and the implications for landslides, hazard assessment, and site investigations. We illustrate how our findings can guide *risk assessment* for geothermal installations and underground storage facilities, as well as *long-term THM behavior* relevant to barriers and reservoirs.

Thank you for your time and consideration. We appreciate the opportunity to have our manuscript reviewed by experts whose research aligns closely with our work in geohazards, engineering geology mapping, risk and reliability, and anisotropic behavior of soils and rocks. We are confident that our research will interest readers seeking to address geotechnical and geological challenges in thermally active subsurface environments.

If you have any questions, please do not hesitate to contact me. We look forward to your feedback.

Sincerely

Saeed Tourchi, PhD

Highlights

Experimental Investigation of Thermal Volumetric Changes in Clays: Unveiling Hidden Controls

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- Stress history dominates thermal volume change in over-consolidated clays.
- High-plasticity clays show larger thermal strains than low-plasticity soils.
- Soil fabric evolves toward elastic behavior under repeated heating–cooling cycles.
- Distinct relations identified between volumetric strain, OCR, and plasticity.
- Findings enhance the design of thermally resilient geo-energy and waste disposal.
- Findings improve risk assessments for geothermal and underground storage projects.

Experimental Investigation of Thermal Volumetric Changes in Clays: Unveiling Hidden Controls

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Abstract

Understanding the thermally induced volumetric behavior of fine-grained soils is central to designing resilient geo-energy infrastructures, including geothermal systems, underground storage facilities, and deep repositories for radioactive waste. In this study, we investigate the coupled thermal-mechanical response of silty clays from Budapest, Hungary, characterized by contrasting plasticity and stress histories. Drained heating and heating–cooling cycle tests were performed in a custom-built, temperature controlled oedometer on both low-plasticity (LP) and high-plasticity (HP) samples. Temperatures ranged from 20°C to 90°C under variable over-consolidation ratios (OCR = 1 to 22). Results confirm that normally consolidated clays exhibit consistent plastic contraction during thermal loading, whereas highly over-consolidated clays reveal a more nuanced response, largely governed by recent stress history. Significantly, reloading events led to contraction in samples where a small elastic expansion might otherwise be expected. High-plasticity samples consistently showed greater thermal strain magnitudes, underscoring the importance of the plasticity index in controlling volume change. Repeated heating–cooling cycles induced mostly plastic strain during the first cycle, transitioning toward elastic behavior and stabilizing volumetric changes by the fourth. These findings offer deeper insight into the mechanics of thermally affected clay deposits, with direct relevance to geological risk assessments for geothermal fields and to the engineered barriers of nuclear waste repositories. By highlighting the pivotal roles of OCR, plasticity index, and stress history, this research contributes to more accurate predictive models and more robust designs for thermally active subsurface infrastructures.

Keywords: Drained Heating, Heating-Cooling Cycles, Fine-Grained Soils, Thermal-Induced Volumetric Changes, Clay, Geotechnical Engineering

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1. Introduction

Thermal and mechanical loads on fine-grained soils have become an increasingly crucial research focus in geo-energy systems. As infrastructure must remain resilient in thermally active environments, it is essential to understand how temperature fluctuations and mechanical stresses affect soil properties and long-term stability. Applications such as geothermal energy systems (Laloui et al., 2006; Faizal et al., 2018; Ng et al., 2016; Aljundi et al., 2024; Liu et al., 2024), nuclear waste repositories (Gens et al., 2009; Tourchi et al., 2021; Bumbieler et al., 2021; Armand et al., 2017; Ballarini et al., 2017), and energy piles (Aresti et al., 2018; Liu and Xu, 2017) expose soils to repeated heating and cooling, potentially altering their deformation characteristics and structural integrity. Similarly, soil-atmosphere interactions in temperate climates (Cui, 2022; Scaringi and Loche, 2022; Melchiorre and Frattini, 2011) and fault zone processes during landslides (Scaringi et al., 2022; Jabbarzadeh et al., 2024; Tourchi et al., 2024; Shibasaki et al., 2017; Sadeghi et al., 2024; Tian et al., 2023; Gong et al., 2024) underscore the broader impact of temperature variations on soil stability. Fine-grained soils, such as clays and silts, are particularly sensitive due to their mineral composition and complex inter-particle interactions (Hoseinimighani and Szendefy, 2022; Hoseinimighani et al., 2023).

Research on temperature-induced changes in soil behavior traces back to foundational works by Gary (1936) and Paaswell (1967), who performed oedometer tests under different thermal conditions. Early studies primarily focused on modest temperature ranges (10–50°C) to account for laboratory-to-field differences; however, modern engineering challenges require dealing with much broader thermal variations, spanning time scales from seconds to centuries. Consequently, current interest extends beyond conventional geotechnical scenarios to applications such as deep geothermal energy extraction, high-level nuclear waste disposal, and energy storage.

A critical factor in understanding soil volume changes under thermal loads is the *Over-Consolidation Ratio* (OCR), defined as the ratio of a soil's past maximum effective stress to its current effective stress. Under drained heating at constant effective stress, NC soils typically exhibit plastic volume contraction. In contrast, highly over-consolidated soils (OCR= 4–8) can show an elastic expansion volume response at lower temperatures before eventually contracting at higher temperatures, often at a *transition temperature* where expansion turns to plastic contraction (Towhata et al., 1993; Coccia and McCartney, 2016; Favero et al., 2016; Mohajerani et al., 2014). Another important distinction involves *intact* (undisturbed) soil samples, which preserve their natural structure and bonding, versus *remolded* samples reconstituted in the laboratory. Intact samples may respond differently under thermal stress due to the presence of in situ inter-particle bonds (Hueckel and Borsetto, 1990; Burghignoli et al., 2000; Hamidi et al., 2024).

Studies generally agree that higher OCR often correlates with a greater tendency for expansion prior to contraction and, in some cases, a higher transition temperature (AbuelNaga et al., 2006a; Baldi et al., 1988; Delage et al., 2000; Vega and McCartney, 2015). Thermally induced changes are influenced by alterations in water viscosity, inter-particle forces, and structural rearrangements within the soil matrix (Hueckel and Borsetto, 1990; Pothiraksanon et al., 2010; Shetty et al., 2019). In addition, plasticity—governed by clay mineralogy and water content—can modify the magnitude and rate of volume changes; high-plasticity clays sometimes exhibit more pronounced initial expansion yet lower net contraction than low-plasticity clays (for over-consolidated soils) (Sultan et al., 2002; Chen et al., 2017). Overall, the literature highlights a multifaceted interaction of stress history, plasticity, and soil fabric in determining thermal volume behavior.

Despite these broad trends, there remain discrepancies that suggest the influence of other critical factors. For example, Cekerevac and Laloui (2004) found constant transition temperatures regardless of OCR, challenging the notion that higher OCR consistently raises the transition point. Hueckel and Borsetto (1990) observed that an intact clay with OCR = 5.7 transitioned at a lower temperature than a remolded clay with OCR = 2.5, indicating that natural structure and inter-particle bonds could outweigh the effects of stress history. Moreover, OCR sample preparation techniques (e.g., reloading versus unloading)—referred to as recent stress history—significantly influence soil behavior. Unloaded samples exhibited expansion at lower temperatures, while reloaded samples primarily contracted upon heating (Towhata et al., 1993; Burghignoli et al., 2000). These unresolved issues hinder the development of universally accurate predictive models for thermally influenced geotechnical systems.

Despite extensive investigations into thermally induced volume changes, this gap in understanding remains evident—especially in undisturbed fine-grained soils where the interplay of stress history, plasticity, and natural bonding has yet to be fully characterized. Consequently, the ability to design reliable, thermally robust foundations and containment systems is undermined by the lack of a comprehensive framework that captures these complex processes. The present study aims to bridge this gap by systematically examining low-plasticity and high-plasticity clays from District 13 and District 8 in Budapest, Hungary, under controlled thermal and mechanical conditions in a custom temperature-controlled oedometer cell.

In particular, this study seeks to:

1. *Investigate* how OCR influences thermal expansion and contraction behaviors in fine clay soil samples.
2. *Quantify* the impact of plasticity on transition temperature and the extent of volumetric changes during drained heating.
3. *Assess* how recent stress history, OCR, plasticity, and thermal cycling jointly shape the soil's volume change mechanisms.

This research contributes to more robust predictive models by clarifying the relative roles of stress history, plasticity, and stress history in determining thermally induced volume changes. Ultimately, the findings will inform improved design strategies for infrastructure subjected to repeated heating and cooling, including energy piles, geothermal projects, and nuclear waste disposal facilities.

Temperature variations significantly affect clay behavior by altering consolidation, mineral-water interactions, and anisotropy. Selected formations with high montmorillonite content show notable thermo-mechanical coupling, where thermal loading alters void ratio, permeability, and shear strength. Understanding these interactions is crucial for designing geo-energy systems, as repeated thermal cycles can cause cumulative deformations and structural failures. Findings from this study impact infrastructure development in Budapest and similar regions. Accurate geological assessments are essential for resilient structure planning, especially in thermally active areas. Insights from District 13 and District 8 soils can guide site selection, material suitability, and performance monitoring, ensuring sustainability and safety in geotechnical engineering projects.

Beyond the local stratigraphy of Budapest, thermal-induced volume changes in clayey formations carry broader geologic implications for geothermal energy installations and underground storage facilities. In geothermal reservoirs—particularly those tapping sedimentary basins with significant clay content—thermal fluctuations may alter porosity and permeability, thus affecting both the efficiency of heat extraction and the potential for induced seismicity. Similarly, for underground facilities storing energy, hydrocarbons, or even high-level nuclear waste, clay barriers or caprock layers are crucial for long-term containment.

Incorporating our experimental findings—specifically on the roles of overconsolidation ratio, plasticity index, and stress history—into the mentioned geo-energy applications can lead to more reliable predictions of deformation and potential fluid migration. Consequently, local site investigations (like those in Districts 13 and 8 in Budapest) have broader geological utility by contributing to refined risk assessments and improved management strategies for thermally active subsurface projects worldwide.

2. Geological Background of Study Area

The study area comprises two distinct regions within Budapest, Hungary: District 13 and District 8. Each region exhibits unique geological and lithological characteristics that significantly influence the engineering behavior of fine-grained soils. District 13 lies within the Pest Plain, a subdivision of the Great Hungarian Plain, and is positioned at the transition between Upper Pleistocene-Holocene fluvioeolian sands (*fQh3-hh*) and Holocene riverine silts (*fQh2al*), as delineated by Hungary's Geological Map. The subsurface profile predominantly consists of sandy, silty clay deposits of Miocene age, with minor intercalations of gravel streaks that reflect fluvial and aeolian transport processes. Soil sampling was conducted at a depth of 13.5 m, where the upper layers, up to 16 m, exhibit a relatively loose structure transitioning to a denser, more consolidated state with increasing depth.

District 8, located within the Pesti Alluvial Fan Microregion, is underlain by Upper Pleistocene-Holocene fluvioeolian sands (*feQp3-hh*), which predominantly consist of fine-grained sediments with occasional sandy interbeds. The grey clay deposits sampled at a depth of 8.5 m correspond to Miocene-aged formations characterized by high plasticity and low permeability. These clayey deposits suggest deposition under low-energy fluvial or lacustrine conditions, resulting in a cohesive matrix with significant consolidation history.

3. Material Properties

As described above, the soils used in this study were fine-grained samples collected from two distinct locations in Budapest, Hungary: District 13 and District 8. These areas represent different geological contexts, offering insights into the behavior of low-plasticity and high-plasticity clays under thermal and mechanical loads. The samples were extracted as undisturbed cores to preserve their natural structure and properties.

District 13 samples (we call LP)—LPs were collected from a depth of 13.5 m, corresponding to a Miocene-age sandy silty clay layer. Classified as CL (low-plasticity clay) under the Unified Soil Classification System (USCS), its index properties are summarised in Table 1. Figure 1a displays the particle size distribution from multiple tests, emphasizing the variability in soil composition and measurements for a more accurate representation of the tested soil samples.

Table 1: Summary of index properties for LP sample

Property	**Symbol**	**Unit**	**Value**
Sat unit weight	γ	kN/m^3	20.4-21.2
Water content	ω	%	18-22
Liquid limit	LL	%	41-46
Plasticity index	PI	%	16-21
Initial void ratio	e_0	-	0.52-0.57
Particle density	ρ_s	g/cm^3	2.586-2.658

District 8 samples (we call HP samples)—HPs were collected from a depth of 8.5 m and identified as a highly plastic grey clay from a Miocene-aged layer. Classified as CH (high-plasticity clay) under USCS, its index properties are also presented in Table 2. The particle size distribution for this sample is provided in Figure 1.

Table 2: Summary of index properties for HP sample

Property	Symbol	Unit	Value
Unit weight	γ	kN/m^3	19.9-20.8
Water content	ω	%	21-27
Liquid limit	LL	%	55-61
Plasticity index	PI	%	35-38
Initial void ratio	e_0	-	0.65-0.67
Particle density	ρ_s	g/cm^3	2.67

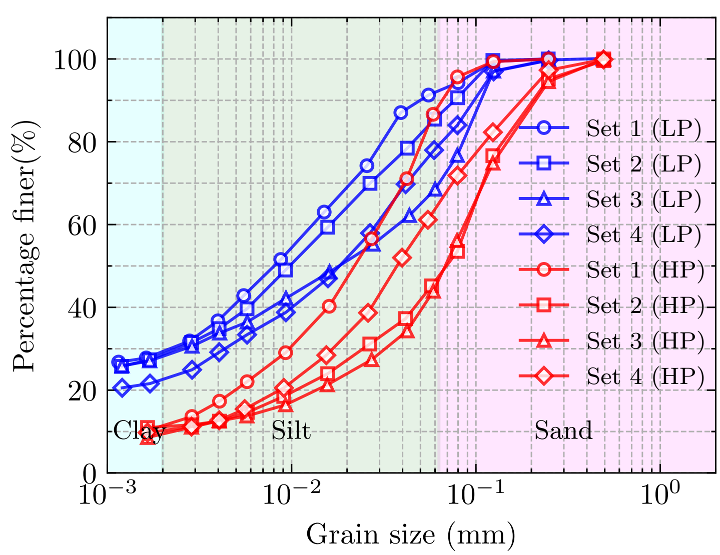

Figure 1: Particle distribution for Sample LP (A) and HP (B) samples.

The groundwater levels during sampling were consistent with the expected local geology. The LP sample's groundwater depth ranged between 6.8 and 9.5 meters, and the HP sample's was approximately 3.5 meters. These data confirm the suitability of the chosen depths for evaluating the behavior of natural, undisturbed clay layers.

4. Experimental Apparatus

The experimental program utilized a temperature-controlled oedometer apparatus specially designed for this study to investigate soil behavior under coupled thermal and mechanical loads. The conventional oedometer cell was modified to incorporate thermal regulation while preserving the core functionality of a standard consolidation setup.

The oedometer cell was surrounded by an electrical heater capable of precise temperature adjustments. The heater was calibrated to deliver a uniform temperature gradient at a rate of 0.3°C/hour, which was critical for maintaining drained conditions and avoiding thermal pore pressure generation. The apparatus was enclosed in an aluminum casing lined with insulating material to minimize heat loss and maintain thermal stability. Three Type K thermocouples were installed—one in contact with the heater and two submerged in the water surrounding the soil sample—to accurately monitor and control the test environment. This setup ensured uniform temperature distribution throughout the test. A water sensor, integrated into the consolidation cell, maintained full saturation during elevated temperature phases by compensating for evaporation through automated water addition. Figure 2 illustrates the modified oedometer cell and its components. Vertical stress was applied using a calibrated lever arm system, with weights placed at varying distances to achieve precise load increments. Vertical displacement was recorded continuously using a Linear Variable Differential Transformer (LVDT) with an accuracy of $1\,\mu$m. The LVDT was connected to a data acquisition system for real-time monitoring.

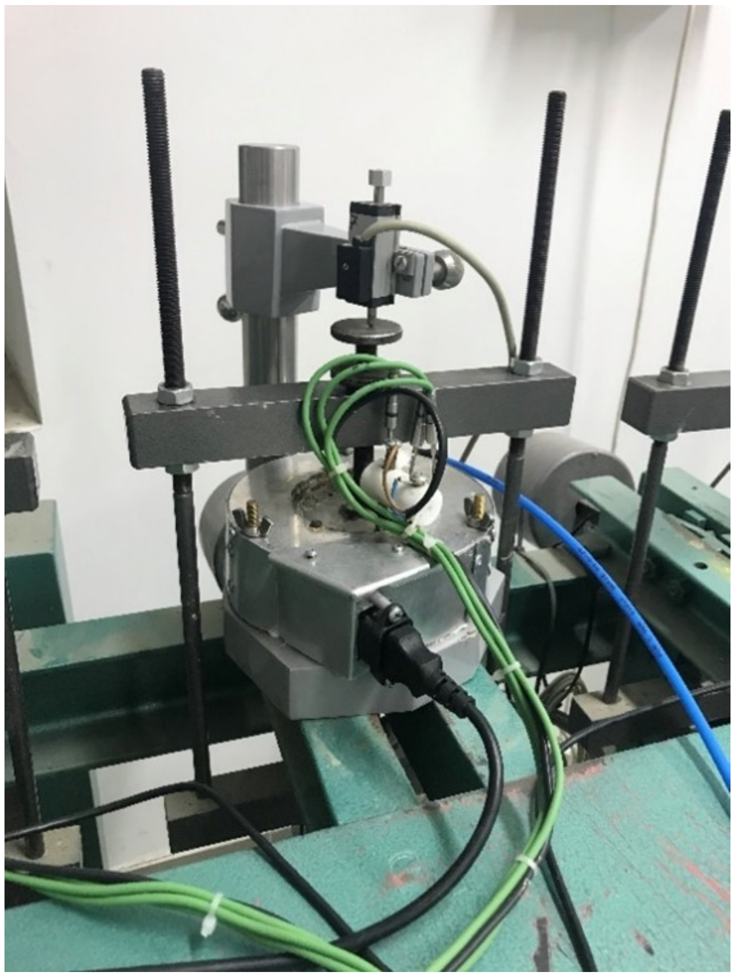

Figure 2: Modified thermal consolidation test device.

5. Experimental Program

The experimental program was designed to investigate the coupled thermal-mechanical behavior of fine-grained soils under drained heating and heating-cooling thermal cycles. The tests evaluated the role of over-consolidation ratio (OCR), plasticity, and stress history in shaping the volumetric response of natural clays.

Drained Heating Tests (h)

This phase of the experimental program focused on understanding the influence of OCR on the volumetric behavior of natural clay samples. Undisturbed samples were first subjected to mechanical preloading to establish specific OCR conditions. These included a normally consolidated state (OCR = 1) and progressively over-consolidated states (OCR = 2, 6, and higher), achieved using controlled incremental loading and unloading processes. The preloading procedures ensured the stress history was systematically varied across the test specimens. The highly over-consolidated samples LP12 and HP22 were prepared differently from the rest of the samples. OC Samples were created using an unloading method. This involved loading the sample and then unloading it to the target stress.

In contrast, samples LP12 and HP22 were not subjected to prior mechanical loading but were only loaded by the weight of the loading cap and are thus not affected by prior unloading. This difference in preparation is essential because the recent stress history of the soil (i.e., whether the sample was loaded or unloaded) can influence its thermal response. While all OC samples experienced unloading as part of testing, samples LP12 and HP22 experienced a recent loading before the heating phase.

Once the desired OCR was achieved, the samples were subjected to thermal loading. The temperature was increased from 25°C to 85°C at a controlled rate of 0.3°C/hour, chosen to maintain drained conditions and avoid the buildup of thermal pore pressures. The effective stress was held constant throughout the heating process. Vertical displacements were continuously recorded using a high-resolution Linear Variable Differential Transformer (LVDT), and volumetric strain was calculated based on the monitored displacement. The mechanical and thermal paths for these tests are summarised in Table 3, while Figure 3 provides a schematic representation of these paths.

Table 3: Summary of drained heating tests.

ID	Loading	OCR	Thermal Loading
LP1	5→1200	1	25→85
LP2	5→1200→600	2	25→85
LP6	5→1200→200	6	25→85
LP12	5	12	25→85
HP1	5→800	1	25→85
HP2	5→1200→600	2	25→85
HP6	5→1200→200	6	25→85
HP22	5	22	25→85

Heating-Cooling Thermal Cycle Tests (TC)

Heating-cooling thermal cycle tests were conducted to evaluate the cumulative effects of thermal cycling on the volumetric behavior of soils. These

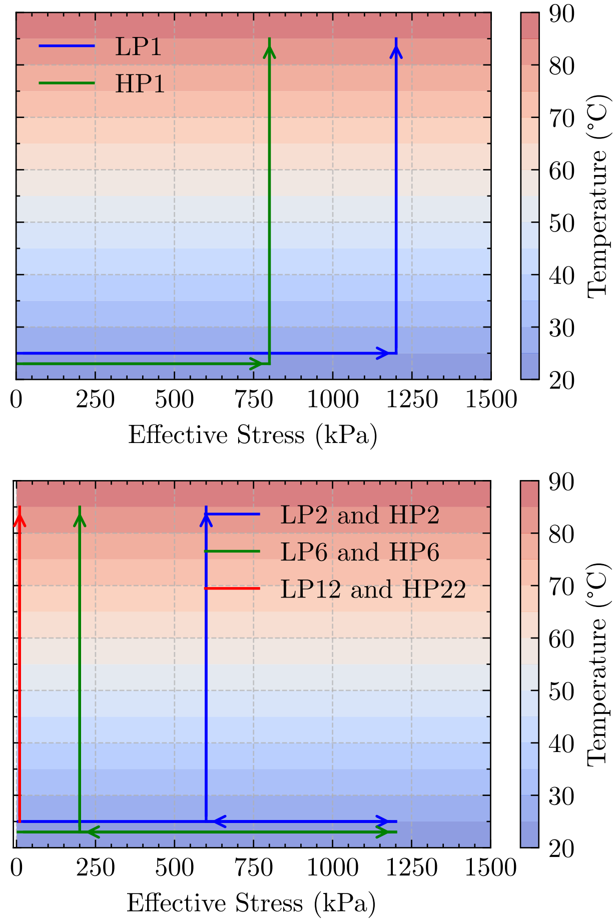

Figure 3: Mechanical and thermal paths for drained heating tests (AH1-BH1 and AH2, AH3, AH4).

tests aimed to distinguish between elastic and plastic deformation components and to assess the stabilization trends over multiple thermal cycles. Samples were initially pre-loaded to specific OCR conditions, similar to those used in the drained heating tests, to ensure consistency in stress history. The thermal cycles alternated between 25°C and 85°C, with each heating and cooling phase conducted at a 0.3°C/hour rate. This controlled thermal rate ensured drained conditions and prevented excess pore pressure development during cycling.

At the end of each heating-cooling cycle, volumetric changes were recorded to evaluate the progressive deformation characteristics of the soils. The thermal paths and loading protocols for these tests are detailed in Table 4, and a graphical depiction of the thermal cycling process is provided in Figure 4.

Table 4: Summary of drained heating-cooling tests.

ID	**Loading**	**OCR**	**Thermal Loading**
LP1	5→1200	1	25→85→25
LP2	5→1200→600	2	25→85→25
LP6	5→1200→200	6	25→85→25
HP1	5→800	1	25→85→25
HP2	5→1200→600	2	25→85→25
HP6	5→1200→200	6	25→85→25

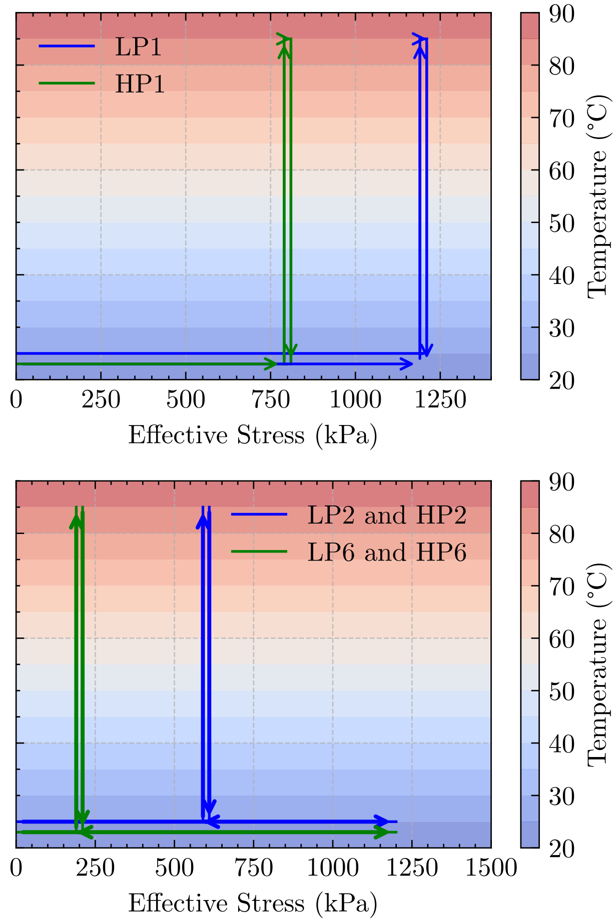

Figure 4: Mechanical and thermal paths for heating-cooling cycle tests.

6. Results and Discussion

6.1. Drained Heating Tests

The thermal volumetric response of selected samples under slow-drained heating is examined in Figures 5a and 5b, which depict volumetric strain versus temperature increment for LP samples and HP samples, respectively. Normally, consolidated samples consistently exhibit contraction during drained heating for both LP and HP samples. This behavior aligns with prior studies (e.g., AbuelNaga et al., 2006b; Baldi et al., 1988).

Previous studies on slightly over-consolidated clay samples, including Pontida silty clay (OCR=2) (Baldi et al., 1988), Kaolin clay (OCR=2) (Cekerevac and Laloui, 2004), and Pasquasia clay (OCR=3.4) (Hueckel and Borsetto, 1990), consistently exhibit purely contractive thermal responses. These behaviors align closely with the observations from samples LP2 and HP2 in this study, reinforcing the understanding that clays with moderate over-consolidation ratios (OCR $\leq$ 3.4) primarily experience volume contraction when subjected to heating.

However, all tested OC samples displayed contraction—a limited initial expansion was observed for HP samples with OCR = 6 and 22, which quickly diminished and transitioned to contraction. These measurements deviate from previous findings, which generally show that highly over-consolidated clay samples typically undergo an initial expansion, followed by contraction. This implies that OCR alone may be insufficient to predict thermal volume change.

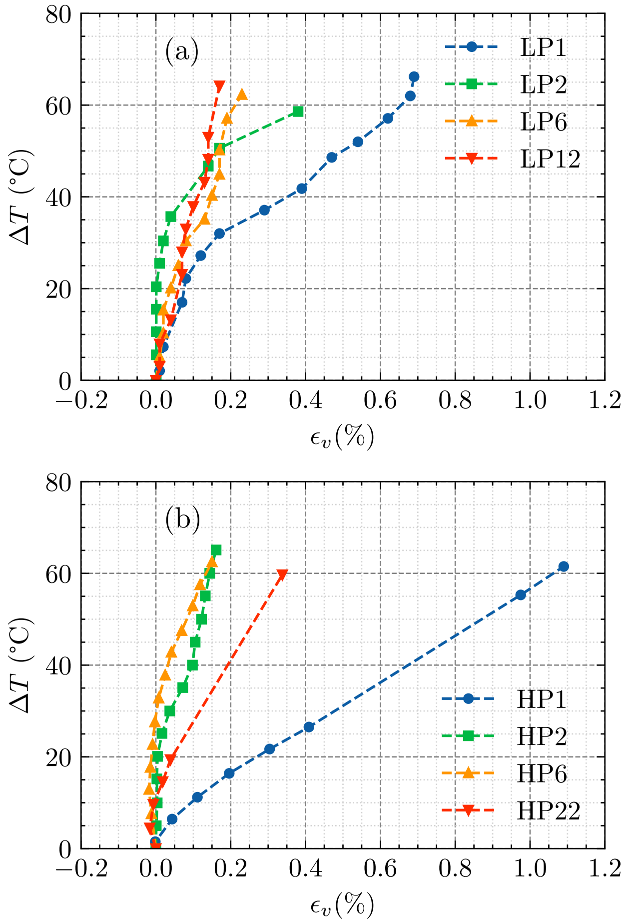

Figure 5: Thermal volume change after drained heating for (a) Low Plasticity (LP) and (b) High Plasticity (HP) samples, illustrating the predominant contraction behavior across different OCRs.

Samples with an OCR = 6 exhibited distinct thermal volumetric behaviors directly influenced by their plasticity levels. Specifically, the low-plasticity sample (LP6) demonstrated significant and consistent contraction during thermal loading, lacking the initial expansion typically expected for this OCR level. In contrast, the high-plasticity sample (HP6) showed only a minimal initial expansion before transitioning to contraction. This deviation from conventional expectations can be attributed to the presence of sand grains within the soil matrix.

Thermal contraction observed in fine soils occurs due to several interrelated mechanisms. Studies have shown that thermally induced pore pressure dissipation under drained conditions leads to volumetric contraction (Delage et al., 2000). Additionally, elevated temperatures reduce the thickness of the double layer, potentially causing particle rearrangement and volume contraction (Campanella and Mitchell, 1968). Another significant factor is the reduction in the viscous shear resistance of pore water with increasing temperature, which enhances particle mobility and structural collapse (Cui et al., 2000).

Thermal expansion, on the other hand, is attributed partly to the thermal expansion of soil constituents (Campanella and Mitchell, 1968) and partly to increased inter-particle repulsion forces (Israelachvili, 1991; AbuelNaga et al., 2007b), which result in the expansion of inter-particle spacing and the formation of larger macropores. These thermal effects, acting synergistically, highlight the complex interplay between mechanical and physicochemical processes in fine soils subjected to thermal loading.

The contraction observed in LP samples, and the lack of expansion in over-consolidated samples suggest that the mineral composition and low-plasticity nature of LP soils dominate their thermal response. This results in limited electrochemical interactions and lower water adsorption capacity. These characteristics reduce the tendency for inter-particle repulsion, allowing other mechanisms responsible for thermal contraction to dominate the thermal volume change. In contrast, HP samples with higher plasticity exhibit a greater capacity for physicochemical interactions and inter-particle repulsion forces. At increased temperatures, these forces amplify, leading to the initial expansion observed in over-consolidated states. However, as temperatures continue to rise, mechanisms such as the thermally induced reduction in double-layer thickness, the reduction in viscous shear resistance, and the dissipation of thermally induced excess pore pressure become dominant, resulting in contraction. This could explain the smaller and less pronounced thermal expansion observed in the over-consolidated HP sample compared to results reported in the literature.

The highly over-consolidated samples, namely LP12 (OCR=12) and HP22 (OCR=22) were subjected to reloading before heating. The rationale for this approach is taken from the studies of Burghignoli et al. (2000) and Towhata et al. (1993), which investigated the effects of different stress histories—namely unloading and reloading—on the volumetric response of soils under thermal loading. Our objective in exploring the impact of stress history through various stress paths was to determine how prior mechanical loading (recent stress history) influences the thermal behavior of clayey soils. By applying unloading and reloading scenarios, we aimed to simulate real-world conditions and evaluate their impact on soil microstructure, void ratios, and volume changes during heating.

Figure 5 revealed NC and slightly over-consolidated samples contract when heated under drained conditions, but some highly over-consolidated samples depart from the classic *initial expansion* expectation. Figure 6 explains this discrepancy by comparing the normalized change in void ratio to the over-consolidation ratio (OCR), incorporating data from both this study and previous work by Burghignoli et al. (2000) and Towhata et al. (1993). By scaling Δe_T by the temperature increment (ΔT), Figure 6 demonstrates that recent stress history—involving unloading versus reloading—shapes the soil's thermal response as much as OCR itself. Normally, consolidated soils consistently contract, but overconsolidated samples can behave similarly if reloaded, showing minimal or no expansion. This confirms that OCR alone is not a definitive predictor of thermal volume change, highlighting the key role of recent loading paths in governing soil behavior under heating.

Additionally, soil plasticity emerged as a significant factor. Samples with higher plasticity (HP1 and HP22) exhibited greater contraction under thermal loading compared to low-plasticity samples (LP1 and LP12). The mineral composition and microstructural properties of these clays facilitate more pronounced particle movement and rearrangement during temperature fluc-

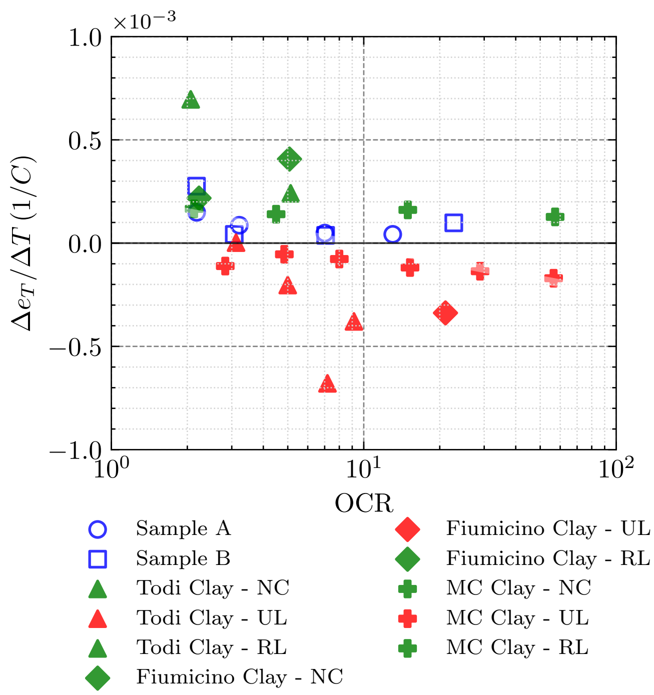

Figure 6: Thermally-induced volume change for Todi and Fiumicino clay (Burghignoli et al., 2000), MC clay (Towhata et al., 1993), and LP sample and B

tuations, making them more susceptible to sustained contractions. Moreover, the effect of plasticity on thermally induced volumetric strain is more pronounced in samples not subjected to unloading, where constant stress conditions allow for a clearer assessment of plastic deformation mechanisms, uninfluenced by elastic rebound or stress-induced volume changes.

To demonstrate the relationship between thermally driven volumetric response and a soil's plasticity, Figure 7 illustrates how a soil's plasticity index (PI) correlates with the normalized thermally induced volumetric strain observed in normally consolidated samples during drained heating. The data exhibits a clear trend of exponentially increasing thermal strain with increasing plasticity index across all tested materials and datasets. This relationship can be modeled by the exponential equation:

$$\varepsilon_{v,T}/\Delta T(\%/C) = 0.0061 \cdot e^{0.378PI(\%)} \tag{1}$$

where $\varepsilon_{v,T}/\Delta T$ represents the normalized volumetric strain, and PI is the plasticity index. This suggests that soils with higher PI values are more susceptible to greater volumetric changes during drained heating, indicating a strong, directly proportional relationship between plasticity and thermal response under specified conditions.

6.2. Heating-cooling thermal cycle (TC)

The thermal volume change of clay samples during the first heating and cooling is shown in Figures 8 for LP and HP samples. For LP samples, the

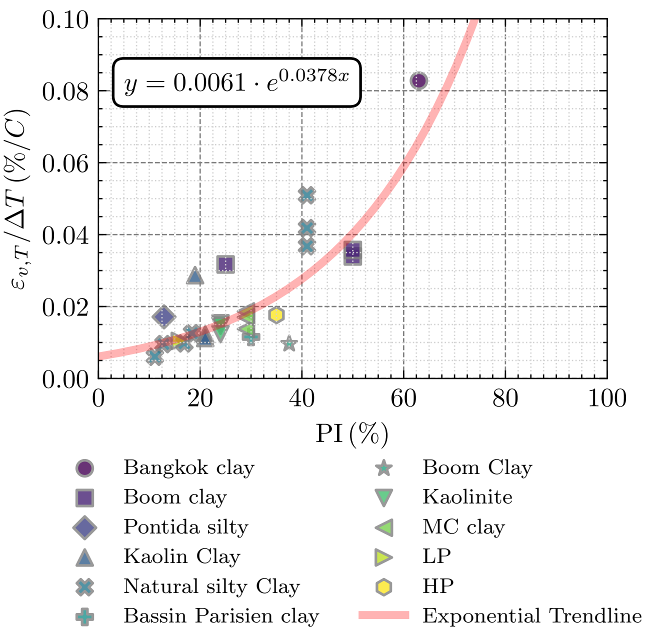

Figure 7: Effect of plasticity on volumetric strain after heating-cooling cycle for normally consolidated samples from literature and this research, including Bangkok clay (AbuelNaga et al., 2006a), Boom clay (Baldi et al., 1988, Robinet et al., 1997, Sultan et al., 2002), Pontida silty (Baldi et al., 1988), Kaolin Clay (Cekerevac and Laloui, 2004, Takai et al., 2016), Natural silty Clay (Di Donna and Laloui, 2015; Shetty et al., 2019), Illite (Plum and Esrig, 1969), Bassin Parisien clay (Robinet et al., 1997), Kaolinite (Shetty et al., 2019), and MC clay (Towhata et al., 1993).

single heating and cooling cycle caused contraction across all consolidation states. The normally consolidated samples exhibited significant plastic and irreversible contraction. As the OCR increased, the extent of plastic contraction decreased notably. The thermal response for higher OCRs (OCR = 6) became primarily elastic, resulting in minimal contraction during the heating-cooling cycle. This progression demonstrates the stabilizing effect of over-consolidation, which enhances the resistance of soil structure to thermally induced deformation.

HP samples—with higher plasticity—demonstrated similar trends but exhibited larger volumetric strains due to their greater thermal sensitivity. These results highlight that higher plasticity leads to greater plastic deformation in normally consolidated states, while increasing OCR progressively reduces permanent contraction, transitioning to predominantly elastic behavior at higher OCR levels. These trends are consistent with the literature (Baldi et al., 1988; Hueckel and Borsetto, 1990; AbuelNaga et al., 2007b; Di Donna et al., 2016; Shetty et al., 2019; Sultan et al., 2002; Takai et al., 2016; Vega and McCartney, 2015).

6.2.1. OCR role

In order to conduct a comprehensive analysis of the volumetric response of fine-grained soils to thermal loading, a diverse dataset is essential. Figure 9 integrates data from both LP and HP Samples and various literature sources.

As expected, the data reveal that NC samples exhibit plastic contrac-

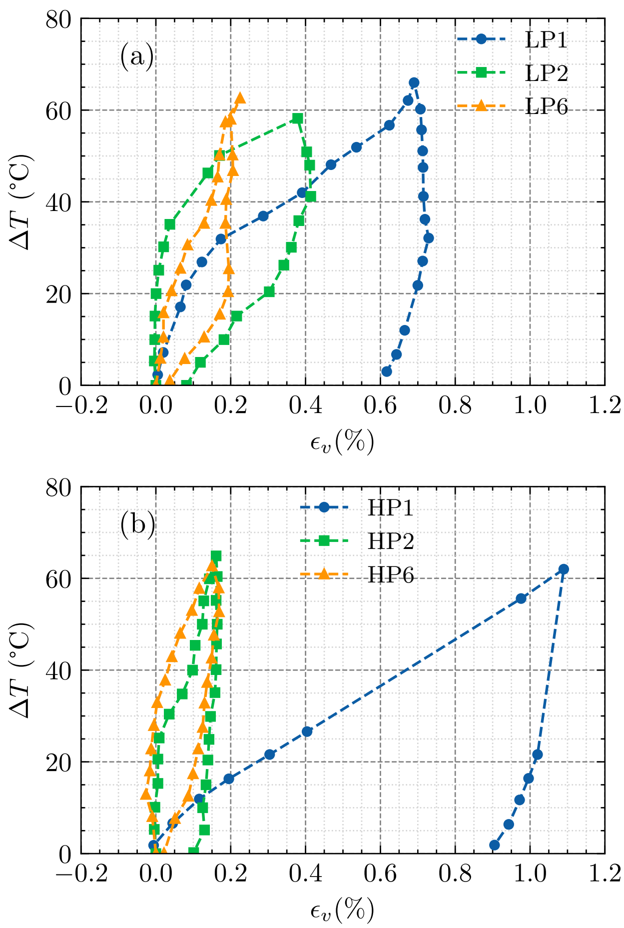

Figure 8: Thermal volume change after drained heating and cooling for (a) Low Plasticity (LP) and (b) High Plasticity (HP) samples, illustrating the differences in contraction and elastic behavior across OCRs.

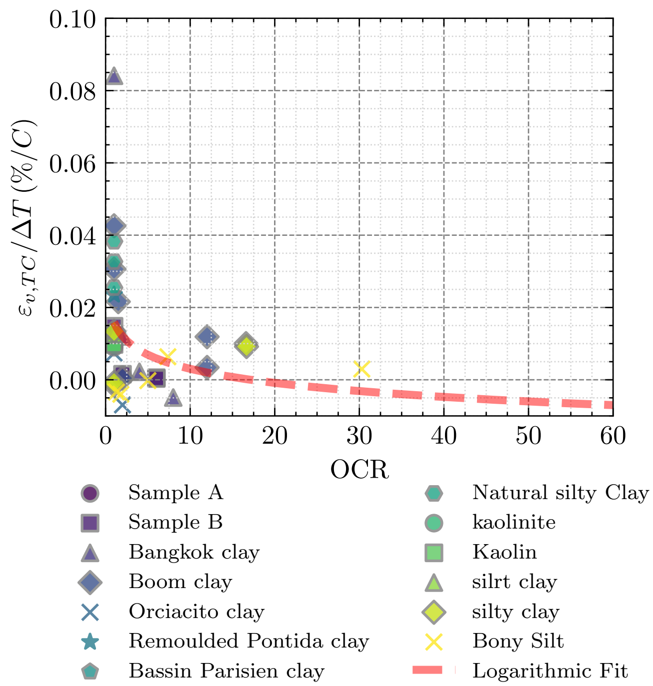

Figure 9: Volumetric strain after heating-cooling cycle for various clay types from literature and this research, including Bangkok clay (AbuelNaga et al., 2007a), Boom clay (Baldi et al., 1988), Remoulded Pontida clay (Hueckel and Pellegrini, 2002), Bassin Parisien clay (Robinet et al., 1996), Natural silty clay (Shetty et al., 2019), Kaolinite (Shetty et al., 2019), Silt clay (Di Donna and Laloui, 2015), and Bony silt (Vega and McCartney, 2015).

tion, consistent with higher strain values. As OCR increases, plastic deformation diminishes. Moderately over-consolidated soils (OCR $\geq$ 2 and $<$ 6) show reduced plastic strain, while highly over-consolidated soils (OCR $\gg$ 6) transition to *elastic-dominated behavior*, exhibiting minimal volumetric change. These trends confirm the stabilizing effect of higher OCR, with over-consolidation limiting plastic deformation and promoting elastic recovery.

However, variations in soil-specific characteristics, such as plasticity, mineralogy, and *stress history* (e.g., unloading vs. reloading), can influence behavior. Some soils in the OCR range of 6–16 display deviations, such as transient elastic expansion or immediate contraction upon heating. These details underscore that OCR alone does not fully capture the complexity of thermal volume change.

To describe the relationship between normalized volumetric strain and OCR, a logarithmic trendline was fitted to the data. This trendline indicates that, for OCR values greater than zero, the thermally induced volumetric strain $\epsilon_{v,TC}$ can be approximated by the function

$$\epsilon_{v,TC} = -0.0052\Delta T \ln(\text{OCR}) + 0.0175\Delta T, \tag{2}$$

where the coefficients -0.0052 and 0.0175 were determined via least-squares regression. The trendline indicates that increasing OCR reduces normalized thermal strain, transitioning from high plastic contraction at low OCR to minimal strain at high OCR. Scatter around the trendline reflects the influence of additional factors such as soil fabric, sand content, and plasticity. This fitted equation highlights the stabilizing effect of over-consolidation on the thermally induced strain, providing a useful framework for understanding the behavior of fine-grained soils under thermal cycling.

6.2.2. Plasticity role (PI)

Building on the preceding discussion regarding the pivotal role of the over-consolidation ratio (OCR) in governing thermally induced volume changes, attention now shifts to plasticity as a further critical parameter in the thermal behavior of fine-grained soils. Figure 10 offers a comprehensive examination of how the plasticity index (PI) influences the volumetric strain ($\epsilon_{v,TC}$) in normally consolidated soils subjected to a full heating-cooling cycle, thereby underscoring the importance of intrinsic soil properties in shaping thermal responses.

A central finding derived from this figure is the robust positive correlation between plasticity and volumetric strain. In particular, soils with higher plasticity indices exhibit markedly greater contraction or deformation under temperature fluctuations. This observation highlights the dominant impact of plasticity in determining the extent of thermally induced volume change, often exceeding even the effect of OCR. For instance, the LP sample (with $PI = 16$) undergoes comparatively modest thermal contraction, whereas the HP sample (with $PI = 35$) experiences notably higher strain, illustrating the pronounced influence of increased plasticity on soil deformation. Similarly, data from Bangkok clay ($PI = 60$) (AbuelNaga et al., 2007b) and Natural silty clay ($PI = 41$) (Shetty et al., 2019) confirm this trend, demonstrating elevated strain values associated with high plasticity.

In order to quantify this relationship, an exponential trendline was fitted to the data in Figure 10, yielding the following equation:

$$\epsilon_{v,TC} = 0.0057\Delta T \cdot e^{0.0394PI} \tag{3}$$

where $\epsilon_{v,TC}$ is the volumetric strain after the thermal cycle, ΔT denotes the temperature increment, and PI represents the plasticity index. This equation reveals that volumetric strain escalates with increasing PI, and it shows strong congruence with both the current dataset and previous findings in the literature, such as Boom clay NC ($PI = 30$) (Robinet et al., 1996) and Remoulded Pontida clay ($PI = 12.9$) (Hueckel and Pellegrini, 2002).

A further analysis of plasticity index ranges elucidates several notable tendencies. Low-PI soils (i.e., $PI < 25$), such as LP sample and Kaolin ($PI = 24$) (Shetty et al., 2019), demonstrate relatively minimal thermal volumetric strain, reflecting a modest sensitivity to temperature changes. Moderate-PI soils ($25 \leq \text{PI} < 40$) begin to exhibit a gradual increase in thermally induced strain, marking a transitional zone. For instance, Bassin Parisien clay ($PI = 20$) (Robinet et al., 1996) and Boom clay ($PI = 30$) (Baldi et al., 1988) illustrate the moderate thermal responses observed in this range. In contrast, High-PI soils ($\text{PI} \geq 40$), exemplified by Bangkok clay ($PI = 60$) (AbuelNaga et al., 2007b) and Natural silty clay ($PI = 41$) (Shetty et al., 2019), undergo pronounced thermal contraction, presumably due to their greater capacity for particle rearrangement and water retention.

The threshold at which a pronounced shift in behavior occurs lies in the range of approximately $PI = 35$–40. Below this boundary, volumetric strain typically remains comparatively moderate, whereas soils surpassing this limit exhibit significantly intensified contraction under heating-cooling cycles. Although some scatter persists—owing to variations in soil mineralogy, fabric, and stress history—the overarching pattern confirms plasticity as a key determinant of soil behavior under thermal loading. For example, Bony Silt ($PI = 4$) (Vega and McCartney, 2015) remains an outlier, showcasing minimal strain even at very low plasticity, further supporting the need for site-specific investigations.

Taken collectively, these results underscore the necessity of considering the plasticity index in the development and enhancement of thermomechanical constitutive models. While current constitutive models within the critical state framework already account for the role of OCR in influencing the volumetric behavior of clays under thermal loading, they do not yet incorporate the influence of the plasticity index. Future advancements in constitutive modeling must address this gap to enhance the predictive capability of existing frameworks and account for the observed correlations between plasticity, OCR, and volumetric strain under thermal loading.

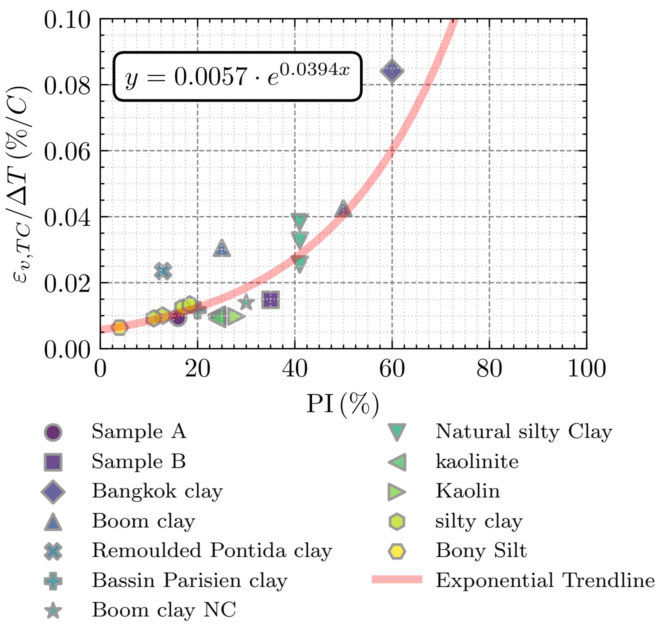

Figure 10: effect of plasticity on volumetric strain after heating-cooling cycle for normally consolidated samples from literature and this research, including Bangkok clay (AbuelNaga et al., 2007b), Boom clay (Baldi et al., 1988; Robinet et al., 1996; Sultan et al., 2002), Remoulded Pontida clay (Hueckel and Pellegrini, 2002), Bassin Parisien clay (Robinet et al., 1996), Natural silty Clay (Shetty et al., 2019), kaolinite (Shetty et al., 2019), silt clay (Di Donna and Laloui, 2015), and Bony Silt (Vega and McCartney, 2015).

6.2.3. *The combined roles of OCR and PI*

To explore the complex thermal volumetric behavior of overconsolidated soils, Figures 11 and 12 focus on two critical parameters: the overconsolidation ratio (OCR) and the plasticity index (PI). In these figures, the thermal volumetric strain ($\epsilon_{v,TC}$) is normalized by the temperature increment (ΔT) and either OCR or PI, providing a consistent basis for cross-sample comparison. This normalization ensures that differences in thermal loading and inherent soil plasticity do not mask key behavioral trends, allowing a clearer assessment of how OCR and PI each affect thermal response.

Figure 11 highlights the influence of OCR, plotted on a logarithmic scale to accommodate the broad range of values. The general trend suggests that soils with relatively low OCR are prone to thermal contraction, whereas those with higher OCR tend toward thermal expansion, in line with the idea that more heavily overconsolidated soils resist volumetric change. The fitted regression line (using log(OCR)) shows an R^2 of about 0.226—indicating a moderate but not definitive predictive capability—and a negative slope for log(OCR). This negative slope implies a decrease in the normalized strain measure as OCR increases, consistent with a shift from contraction-dominated to expansion-dominated behavior. The scatter in the data, however, underscores that OCR alone cannot fully explain thermal volumetric changes, likely due to additional factors such as plasticity and mineral composition.

Figure 12 examines the effect of PI, with thermal volumetric strain nor-

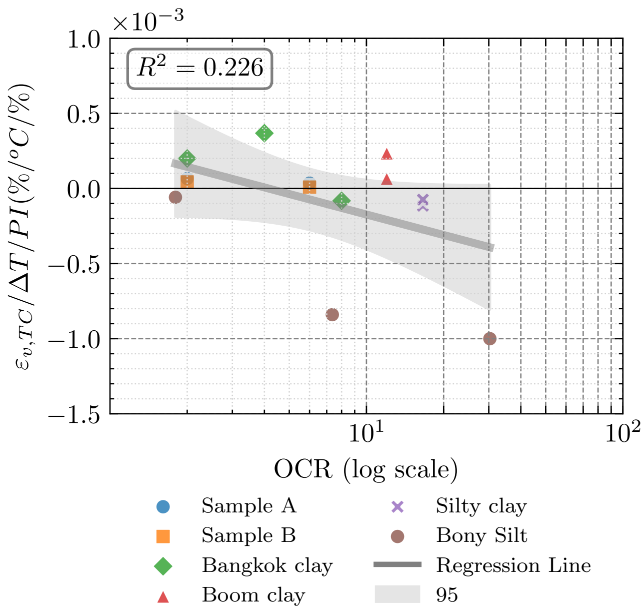

Figure 11: Effect of OCR on normalized volumetric strain for overconsolidated samples, including data from this study (Silty clay, Bony Silt) and literature (Bangkok clay (Abuel-Naga et al., 2007b), Boom clay (Sultan et al., 2002), Silty clay (Di Donna et al., 2016), Bony Silt (Vega and McCartney, 2015)).

malized by ΔT and OCR. Compared to OCR, PI offers a similarly moderate predictive power (with an R^2 of about 0.212). The positive slope in the regression model indicates that the normalized strain measure increases with PI. In practical terms, however, high-PI soils typically experience more pronounced contraction, especially under thermal loading. This apparent disconnect between the slope and the observed contraction can stem from how strain normalization and other soil-specific factors (e.g., structure, mineralogy) interplay with PI in the statistical fit. Despite that nuance, soils like highly plastic Bangkok clay (PI $\approx$ 60%) reliably show considerable thermal contraction, whereas low-PI soils (e.g., Bony Silt, PI = 4%) exhibit minimal or slightly expansive tendencies under similar conditions.

While neither regression achieves a high level of explanatory power, the results confirm that both OCR and PI significantly affect thermal volumetric strain. The following simplified models encapsulate the relationships:

$$\frac{\epsilon_{v,TC}}{\Delta T \cdot \mathrm{PI}} = A \log(\mathrm{OCR}) + B \quad \text{(Figure 11)} \tag{4}$$

$$\frac{\epsilon_{v,TC}}{\Delta T \cdot \mathrm{OCR}} = C\,\mathrm{PI} + D \quad \text{(Figure 12)} \tag{5}$$

Here, A, B, C, and D are regression coefficients obtained from curve-fitting. Although the data shows that OCR can delineate the transition between contraction and expansion, PI remains an equally important predictor of thermal response. Indeed, high-PI soils may still undergo notable contraction even at high OCR, highlighting the need to account for plasticity when modeling thermal soil behavior. Consequently, conventional models that focus primarily on OCR should incorporate PI for better accuracy in geotechnical design, especially for scenarios involving thermally induced volume change.

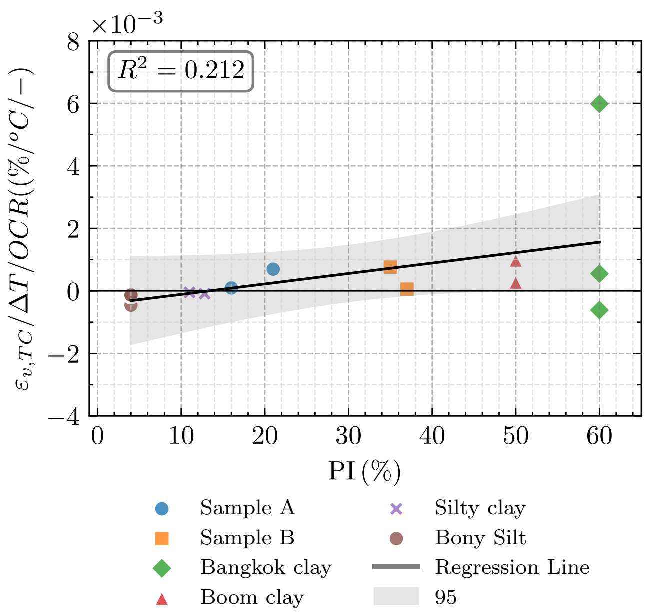

Figure 12: effect of plasticity on normalized volumetric strain for overconsolidated samples, including data from this study (Silty clay, Bony Silt) and literature (Bangkok clay (AbuelNaga et al., 2007b), Boom clay (Sultan et al., 2002), Silty clay (Di Donna et al., 2016), Bony Silt (Vega and McCartney, 2015)).

6.2.4. Thermal Cyclic behavior

The response of the samples to repeated thermal cycling was investigated by subjecting them to drained heating and cooling cycles while maintaining a constant effective stress. Figure 13a illustrates the volumetric strain response of LP1. The initial heating phase results in a significant contraction, while the subsequent cooling phase shows partial recovery, with a noticeable plastic deformation evident at the end of the first cycle. Further heating and cooling cycles lead to progressively smaller volumetric changes, with the overall contraction diminishing with each cycle. This pattern suggests that the sample undergoes a decreasing rate of plastic deformation, moving towards a more elastic behavior as the number of thermal cycles increases. Figure 13b presents the volumetric strain behavior of sample LP6. In contrast to the normally consolidated sample, the strain response of the overconsolidated sample is comparatively smaller. Additionally, the extent of contraction during the heating phases and the partial recovery during cooling phases is considerably less when compared to 13a.

Figure 14 presents the volumetric strain responses of Sample HP under different overconsolidation ratios (OCR) when subjected to repeated drained heating and cooling cycles. Figure 14a depicts the behavior of a normally consolidated sample (HP1) under thermal cycling. The sample exhibits similar contraction during heating phases and partial recovery during cooling phases, as seen in the normally consolidated sample of LP1, as discussed previously. As the number of thermal cycles increases, the changes in volumetric strain become less pronounced, indicating a reduction in plastic deformation and a trend toward stabilization. Figure 14b illustrates the thermal cycling response of a moderately overconsolidated Sample B (HP2). The volumetric strain range is markedly reduced compared to the normally consolidated

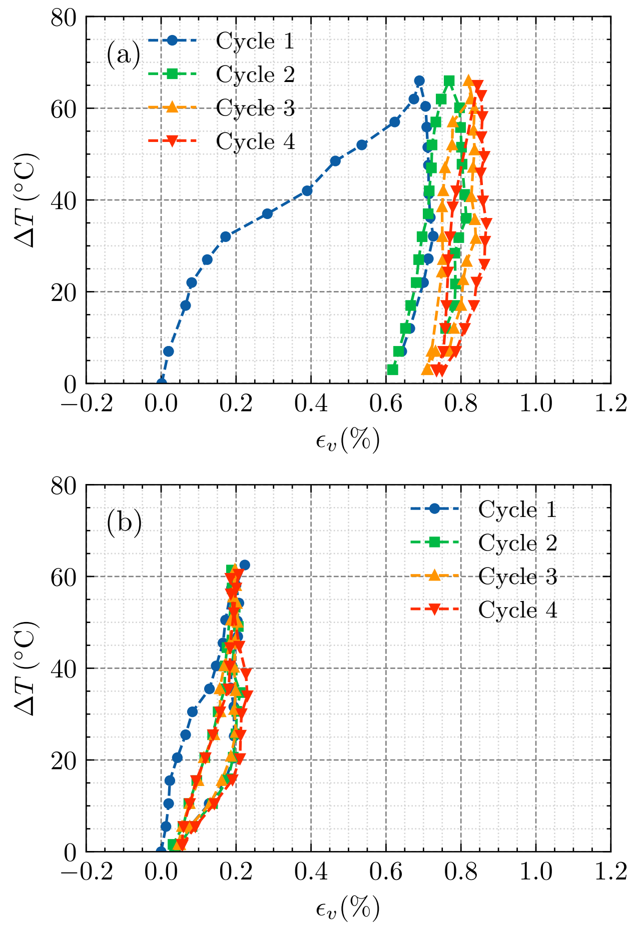

Figure 13: Thermal-induced plastic volumetric strain (ϵ_v) versus temperature change (ΔT) for (a) LP1 and (b) LP6 samples under cyclic thermal loading.

case. The overall contractive behavior reduces substantially for each subsequent thermal cycle, and the response seems largely elastic. Figure 14c shows the results for a highly over-consolidated HP sample (HP6). The overall strain variations are significantly reduced when compared with the previously discussed cases. The sample exhibits near-elastic behavior from the outset, showing immediate and almost complete recovery of deformation from the initial heating cycle with negligible residual volume change.

The contraction and recovery phases show that a significant degree of stabilization occurs after the first thermal cycle. Furthermore, it seems that thermal strain tends to stabilize after the 4th thermal cycle, and soils tend to enter elastic behavior even in the normally consolidated state. These results highlight the critical role of overconsolidation in influencing the thermal response of fine-grained soils. As the OCR increases, the tendency for irreversible plastic deformation under thermal cycling decreases. Higher values of OCR seem to enhance the elastic response, while the magnitude of volume change becomes increasingly suppressed, suggesting the influence of stress history on the structure and behavior of the tested material.

To quantify the progressive accumulation of volumetric strain resulting from repeated thermal cycling, Tables 5 and 6 provide a detailed breakdown of the induced volumetric strains at the end of each heating and cooling phase for the LP sample and HP sample, respectively, under different initial OCR conditions. As illustrated previously in Figures 13–14, the overall volume change and rate of plastic deformation for a given soil was closely influenced

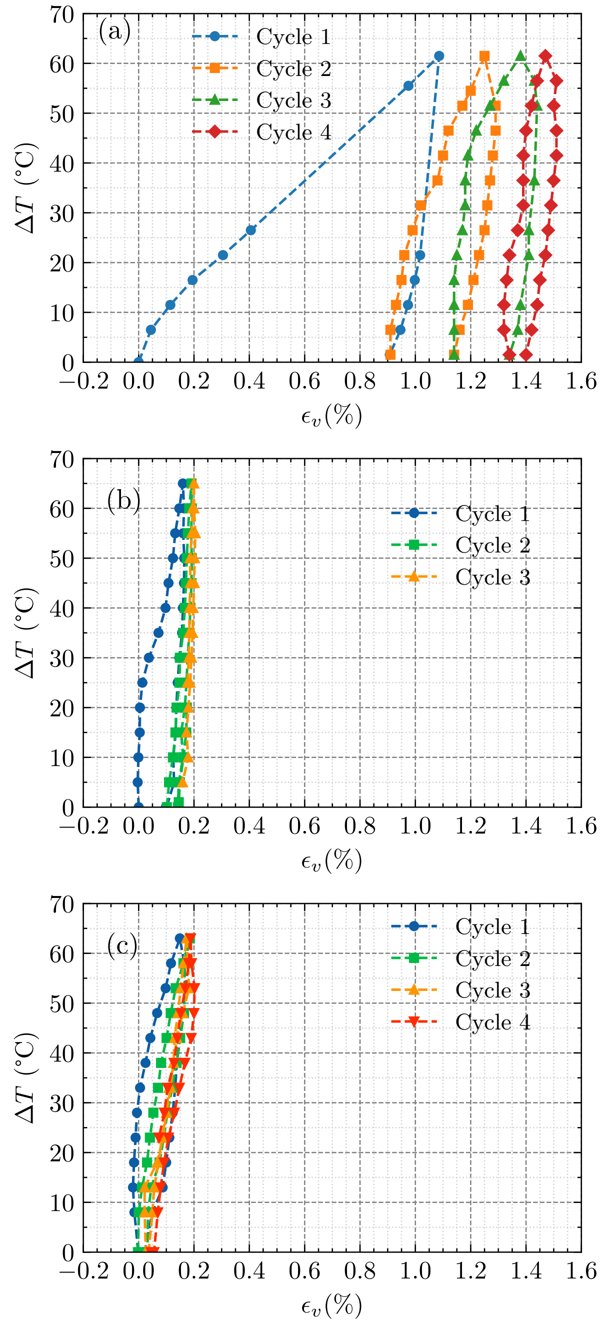

Figure 14: Thermal-induced plastic volumetric strain (ϵ_v) versus temperature change (ΔT) for the HP1, HP2, and HP6 samples under cyclic thermal loading.

by OCR. These values complement that information with quantitative measurements. Table 5 outlines the accumulating strains for the LP sample (low plasticity clay) through four thermal cycles, contrasting a normally consolidated sample (OCR=1) against an overconsolidated sample (OCR=6). A consistent contractive trend is apparent upon every heating and subsequent recovery of some of the volume in every cooling step of the process, with magnitudes gradually reducing after each cycle.

Table 5: Accumulating strain, $\varepsilon_v(\%)$ during heating-cooling cycles for LP sample.

Cycle	**Process**	**OCR=1**	**OCR=6**
1	heating	0.69	0.22
	cooling	0.62	0.04
2	heating	0.77	0.19
	cooling	0.71	0.05
3	heating	0.82	0.20
	cooling	0.73	0.05
4	heating	0.84	0.21
	cooling	0.74	0.05

Table 6 presents the accumulating strains for HP sample (high plasticity clay) across four thermal cycles, contrasting normally consolidated (OCR=1), and an overconsolidated state (OCR=2 & 6). A more significant volumetric response is observed in this sample when compared to the low plasticity material in Table 5 for OCR=1 samples, which is also discussed earlier with regard to Figure 14. While the trends of the thermal loading cycles in the HP sample under different OCR conditions align with the trends of the LP sample in their corresponding OCR conditions, it is observed that the overconsolidated samples with a higher OCR show negligible overall changes after one thermal cycle compared to a considerably reduced accumulated strain after multiple cycles when the sample had a lower OCR condition.

Table 6: Accumulating strain, $\varepsilon_v(\%)$ during heating-cooling cycles for HP sample.

Cycle	**Process**	**OCR=1**	**OCR=2**	**OCR=6**
1	heating	1.09	0.16	0.15
	cooling	0.91	0.10	0.02
2	heating	1.24	0.18	0.16
	cooling	1.14	0.14	0.05
3	heating	1.37	0.20	0.16
	cooling	1.33	0.16	0.07
4	heating	1.47		0.19
	cooling	1.40		0.07

In both sample groups, the cumulative plastic deformation during each successive heating cycle decreases, as each subsequent cooling cycle only restores some volume back to the sample, and the rate of plastic deformation noticeably reduces after each cycle. Figure 15, representing data from the present study combined with a comparable dataset available in published form, demonstrates that plastic components of volumetric strains are most prominent during the early cycles of repeated drained heating on normally consolidated samples, where material-specific changes (linked with Plasticity Index), exhibit notable variations in the magnitude of deformations at first phases followed by reduced change rates after subsequent phases.

Data generally confirms reduced changes over thermal treatment through further cycling for every test series used, irrespective of material type or

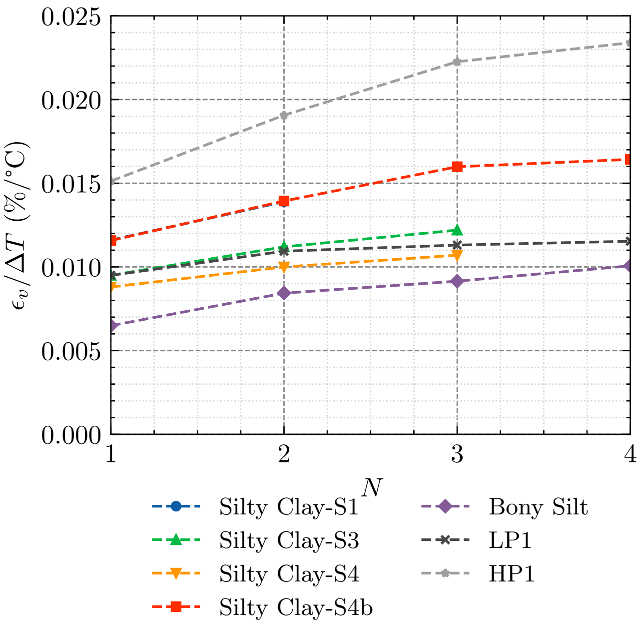

Figure 15: Relationship between the normalized plastic strain increment per degree Celsius and the number of thermal cycles (N) for various soil types. The plot compares silty clays (S1, S3, S4, S4b) from (Di Donna and Laloui, 2015), Bony Silt from (Vega and McCartney, 2015), and two newly tested samples (Samples LP1 and HP1).

values showing reduction and trend toward an elastic like behavior with progressive cycle number but mostly being dominant when plasticity properties are high. The results indicate that thermal volume change stabilizes after the 4th thermal cycle or before the 5th cycle. Furthermore, the incremental plastic deformation during each heating-cooling cycle appears to increase with higher plasticity.

7. Conclusions

This research provides a comprehensive experimental investigation into the thermally induced volumetric behavior of fine-grained soils, focusing on the coupled effects of over-consolidation ratio (OCR), plasticity, and stress history. Key findings include:

- **Stress History Dominance over OCR in Over-Consolidated Clays**: Contrary to expectations based solely on OCR, the recent stress history, specifically reloading, significantly influenced the behavior of over-consolidated samples. Reloaded clays contracted upon heating rather than undergoing initial expansion. This indicates that current models emphasizing only OCR for thermal volumetric change are inadequate.

- **Plasticity as a Key Driver of Volumetric Strain**: The plasticity index (PI) was revealed as a pivotal parameter. High-plasticity clays exhibited substantially larger plastic contractions, greater total volumetric changes, and slower stabilization rates under thermal cycling compared to low-plasticity clays with the same OCR values. These observations underscore that material-specific parameters dominate the magnitude and rates of volume change.

- **Quantified Relationships with OCR and PI**: Logarithmic relationships were quantified to express volumetric strain as a function of temperature change, OCR and PI.

- **Repeated Thermal Cycles Stabilisation**: Repeated thermal cycles induced a gradual decrease in cumulative plastic strain, highlighting that a major portion of the total thermal change was accrued within the first few cycles (less than five thermal cycles) in most samples. Clays trended toward a more elastic behavior with increased cycle counts. Overconsolidated soils stabilized more quickly than their normally consolidated counterparts and showed greater elastic recovery.

- **Interactive Effects of OCR, PI, and Loading Path**: Data synthesis demonstrates that thermal behavior is governed by an interplay between OCR, PI, and recent stress path (reloading or unloading), contradicting conventional assumptions that OCR is the dominant parameter. The study highlights that PI has a significant influence in modifying the contraction of highly over-consolidated soils. Even with very high OCRs, high PI soils can exhibit notable contraction, while the thermal sensitivity of soils at low OCR depends heavily on PI.

Findings from this study provide compelling evidence for reevaluating existing thermo-mechanical constitutive models to specifically include plasticity alongside stress history (including the effects of reloading) for improved predictive capability in thermally active geo-energy applications. Future research should utilize these findings to refine constitutive models for better prediction of soil behavior in diverse real-world scenarios.

The insights gained from our thermo-mechanical tests have practical applications for geologic risk assessments in various subsurface engineering projects. Clays subjected to cyclic heating (e.g., in geothermal energy extraction or seasonal underground thermal energy storage systems) may undergo progressive deformation or develop thermally induced microcracks, potentially altering permeability and mechanical strength. This phenomenon becomes particularly relevant in regions with clay-rich strata similar to those of District 8 in Budapest, where high-plasticity minerals magnify thermally triggered volumetric changes. By matching the OCR- and PI-dependent strain models with specific lithologies, site engineers can more reliably account for the cumulative effects of temperature during facility operations. This expanded viewpoint not only mitigates the potential for unexpected ground movements but also refines the safety margins necessary for structure integrity in the subsurface. Overall, our experimental outcomes bridge the gap between small-scale laboratory characterizations and large-scale geologic risk management, particularly where thermally active systems interact with fine-grained formations.

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Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Saeed Tourchi reports financial support was provided by University of Luxembourg. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.