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Thermally induced transition from expansive clay to a frictional granular state: An experimental investigation

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ABSTRACT

Expansive soils pose persistent challenges to geotechnical design due to their high swelling potential and sensitivity to moisture variations. Thermal stabilization has recently emerged as a promising alternative to conventional chemical treatment, yet its implications for soil strength mechanisms remain insufficiently quantified. This study evaluates the effectiveness of extreme thermal stabilization on a high-plasticity, kaolinite-rich expansive clay, specifically focusing on the evolution of its mechanical strength and shear parameters. Soil specimens were subjected to controlled thermal treatment at 200°C, 400°C, and 600°C for durations of 15, 30, and 120 minutes, followed by systematic evaluation through unconfined compressive strength (UCS) and direct shear tests (DST). Complementary analyses of grain size distribution, consistency limits, and compaction characteristics were conducted to interpret the observed mechanical responses. The results demonstrate that increasing temperature induces a substantial transformation of the soil fabric, marked by aggregation of clay particles into stable, sand-sized clusters and a reduction in plasticity index (PI) from 27.0 to 2.94 at 600°C. While extreme heating led to a substantial reduction in UCS; reflecting the loss of cohesive clay bonds; it simultaneously produced a marked increase in shear resistance under confinement, with the internal friction angle rising from 23.15° to 50.19°. Free swell potential was progressively suppressed and effectively eliminated at 600°C, confirming the permanent mitigation of expansive behavior. The findings highlight a fundamental shift in strength mechanisms from cohesion-dominated to friction-controlled behavior, demonstrating that thermally treated expansive clay can function as a granular-like material with high shear resistance under confinement. These results provide critical insight into the rational use of thermal stabilization in geotechnical applications involving expansive soils.

1. Introduction

Expansive soils constitute a persistent and well-documented challenge in geotechnical engineering because of their pronounced sensitivity to moisture variations. These soils are typically rich in hydrophilic clay minerals, including montmorillonite and kaolinite, which undergo substantial volumetric expansion upon wetting and contraction during drying cycles. Such behavior often leads to differential ground movements that manifest as cracking, uplift, and loss of serviceability in foundations, pavements, and earth-retaining structures. Devkota *et al.* (2022) emphasized that failure to adequately account for these volume changes in design can result in significant structural damage and premature infrastructure deterioration. On a global scale, the economic consequences of expansive soil–related distress are substantial, with reported annual losses exceeding USD 23 billion, highlighting the urgency of developing reliable and sustainable mitigation techniques.

Chemical stabilization using cementitious binders, most notably lime and Portland cement, has traditionally been adopted to control soil expansiveness (Eldemary, 2023; Goutham and Krishnaiah, 2020). While these methods have demonstrated effectiveness in reducing plasticity and swelling, their long-term applicability has increasingly been questioned. As noted by previous studies, concerns related to high carbon emissions associated with cement production, coupled with the risk of deleterious reactions in sulfate-bearing soils, have motivated the exploration of alternative stabilization approaches (Alsabhan and Hamid, 2025; Faridi and Arabhosseini, 2018; Hamid *et al.*, 2022). Within this context, thermal stabilization has gained attention as a viable method capable of fundamentally modifying the mineralogical and mechanical characteristics of clay soils through controlled heat treatment (Alsabhan *et al.*, 2025; Alsabhan and Hamid, 2025; Rahil *et al.*, 2020; Yao *et al.*, 2022).

The application of thermal techniques in soil stabilization is not a recent development. Early field-scale implementations by Beles *et al.*, (1958) and Litvinov (1960) involved the combustion of fuel within boreholes, generating temperatures approaching 800°C to stabilize unstable slopes. These studies demonstrated that exposure to high temperatures could induce irreversible mineral transformations, resulting in long-term reductions in soil deformability. Advancements in laboratory-based investigations subsequently refined these concepts. Wang *et al.* (2008) reported that heating kaolin to approximately 400°C and bentonite to 600°C was sufficient to suppress expansive behavior

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by altering the crystal structure of the clay minerals. Comparable outcomes were reported by Kabubo *et al.* (2017), who observed that black cotton soil heated to 600°C exhibited a 15% increase in maximum dry density (MDD), accompanied by reductions exceeding 30% in both plasticity index (PI) and swelling potential.

Subsequent studies have examined the evolution of soil strength characteristics under elevated temperatures. Joshi *et al.* (1994) demonstrated that heating clay soils to temperatures as high as 700°C resulted in compressive strength gains of up to 300%, primarily attributed to dehydroxylation and the development of a partially sintered soil matrix. From an in-situ perspective, Park *et al.* (2012) employed electric pipe heaters to thermally treat near-surface soils, reporting that heating to only 110°C increased bearing capacity by more than three times due to the formation of a stiffened zone surrounding the heat source. The influence of treatment configuration was further highlighted by Rahil *et al.* (2020), who showed that borehole spacing plays a critical role in achieving uniform reductions in plasticity, with closer spacing producing more consistent stabilization outcomes.

More recent research has focused on improving the efficiency and adaptability of thermal stabilization methods. Yao *et al.* (2022) investigated microwave heating, noting that its direct interaction with pore water facilitated rapid strength development, with reported increases of up to 27 times and near-complete elimination of expansion at temperatures exceeding 500°C. Hybrid approaches have also been explored. Al-Swaidani *et al.* (2018) demonstrated that combining thermal treatment with lime addition reduced swelling pressure by more than 85%, indicating a synergistic interaction between physical and chemical stabilization mechanisms. Similarly, Tamiru *et al.* (2025) reported that for certain expansive clays, noticeable improvements in engineering behavior begin at approximately 400°C, with complete loss of plasticity and swelling pressure observed at 600°C.

Building upon this growing body of evidence, Alsabhan *et al.* (2025) recently investigated a high-plasticity expansive soil obtained from the Al-Ghat region. Their study demonstrated that controlled heating to 600°C entirely eliminated the soil's expansive behavior, with the free swell index decreasing from 6% to nearly zero and decreasing the swell pressure from 250 kPa to zero. Mineralogical and microstructural analyses using X-ray diffraction (XRD) and scanning electron microscopy (SEM) revealed that these changes were governed by the dehydroxylation of kaolinite to metakaolin and the agglomeration of clay particles into coarser, fused structures.

Although Alsabhan *et al.* (2025) demonstrated that controlled thermal treatment effectively suppresses the swelling behavior of Al-Ghat clay and clarified the associated mineralogical and microstructural transformations, that study did not systematically quantify the resulting mechanical response. In particular, the effects of heating on unconfined compressive strength (UCS), direct shear behavior, and the Mohr–Coulomb strength parameters, namely cohesion and internal friction angle, remain insufficiently documented. Addressing this gap is essential for assessing whether thermal treatment can be translated from a swelling-mitigation approach into a practical ground-improvement method for geotechnical design. Therefore, the present study extends the earlier work by providing a new mechanical dataset for thermally treated Al-Ghat clay, including UCS measurements, direct shear test (DST) results under multiple normal stresses, and the corresponding shear strength parameters. In addition, this study offers a broader interpretation of the thermal treatment effect by examining how heating alters the soil response from that of an expansive cohesive clay toward a more friction-controlled material. Supporting gradation, Atterberg limits, and compaction characteristics are also presented to aid interpretation of the observed mechanical behavior.

2. Experimental program

2.1 Soil procurement and characterization

The experimental program utilized expansive clay sourced from Al-Ghat region, located approximately 250 km northwest of Riyadh, Saudi Arabia. To ensure the test material was representative of the site, disturbed samples were collected from multiple spatial coordinates and thoroughly homogenized into a single bulk sample. The preparation protocol involved air-drying the material followed by pulverization; the soil was subsequently screened through a 425 μm (No. 40) sieve to achieve granular uniformity and stored in sealed containers to prevent moisture fluctuations.

Geotechnical indexing classifies the soil as high-plasticity clay (CH) according to the unified soil classification system (USCS) and A-7-6 according to American Association of State Highway and Transportation Officials (AASHTO) standards, confirming its high clay content and susceptibility to volume change. Mineralogical assessment via XRD identified kaolinite as the primary clay mineral phase, accompanied by minor illite fractions (Alsabhan *et al.*, 2025). Distinctively, montmorillonite was not detected in the mineralogical profile, indicating that the expansive behavior is driven primarily by the kaolinite-illite matrix rather than smectite group minerals.

2.2 Specimen preparation and experimental protocols

Thermal treatment strategy was executed using a programmable high-temperature electric furnace (Matest), designed with a thermally insulated chamber to ensure uniform internal heat distribution up to 1000°C. The experimental program adopted a stepped heating regimen, subjecting the expansive clay to target temperatures of 200°C, 400°C, and 600°C with a retention time of 15, 30, and 120 minutes at each plateau. These thermal thresholds were selected to represent distinct treatment levels that, according to previous studies on kaolinitic expansive soils and earlier XRD/SEM analysis of the same Al-Ghat clay (Alsabhan *et al.*, 2025), are associated with moisture loss at lower temperatures, onset of mineralogical alteration at intermediate temperatures, and the fully transformed high-temperature condition at 600°C. In the context of the present study, the 600°C condition was selected as an upper-bound thermal stabilization level intended to capture the end-member response of the clay following essentially complete and irreversible mineralogical transformation. Accordingly, this temperature is used here to define the fully transformed state of the material, rather than to suggest that routine field applications would necessarily require uniform in-situ heating to 600°C. Visual inspection of the post-treatment samples indicated distinct chromatic and textural shifts, providing preliminary evidence of structural alteration.

After completion of the designated heating period, the furnace was switched off and the treated soil was allowed to cool gradually to room temperature inside the furnace before removal. Once cooled, the material was removed from the furnace and immediately placed in sealed plastic bags to minimize uncontrolled moisture exchange with the laboratory environment. For subsequent specimen preparation, distilled water was added to achieve the target moisture content, taken as the optimum moisture content (OMC) corresponding to each treatment condition. The moistened soil was then mixed thoroughly and stored in sealed plastic bags for at least 24 h to allow moisture equilibration prior to compaction and mechanical testing.

2.3 Compaction and sample reconstitution

Due to the limited volume of soil available following thermal treatment, compaction characteristics; specifically MDD and OMC; were established using the reduced-scale compaction method proposed by Sridharan and Sivapullaiah (2005). This technique, which employs a 1.0 kg hammer and 36 blows per layer, was developed primarily for fine-grained soils and requires substantially less material than the Standard Proctor test American Society for Testing and Materials (ASTM D698). In the present study, it was adopted to obtain condition-specific MDD and OMC values for specimen reconstitution and for comparative assessment of the influence of thermal treatment on compaction behavior. Because the soil underwent substantial thermally induced changes in gradation and plasticity, the resulting compaction parameters should be interpreted within the context of this experimental program rather than as a direct substitute for ASTM D698 field-control values for every thermal condition. For mechanical testing, the conditioned soil was compacted at the corresponding OMC for each treatment condition. After moisture equilibration, specimens were prepared and tested in accordance with the UCS and DST procedures described below.

2.4 Mechanical testing program

Fig. 1 illustrates the experimental setup used for both the DST system and the UCS testing machine. The mechanical behavior of the untreated and thermally treated soil was evaluated using UCS and DST in accordance with ASTM standards. Unconfined compressive strength tests were performed following ASTM D 2166, in which cylindrical specimens were subjected to monotonic axial loading at a constant strain rate of 0.5 mm/min. The resulting stress–strain response was recorded continuously, and the peak axial stress attained during loading was taken as the UCS. Although UCS is traditionally most appropriate for cohesive soils, it was retained in the present study as a comparative indicator of the residual self-supporting strength of the material after thermal treatment. Because the specimens were compacted at the corresponding OMC rather than tested in a fully saturated state, the measured UCS values may also reflect suction effects. Accordingly, UCS is interpreted here as a comparative index of unconfined strength evolution with heating, rather than as a complete effective-stress characterization of the treated soil. For this reason, consolidated drained DST was also performed to provide a confinement-dependent assessment of shear behavior. In this context, UCS was used primarily to quantify the progressive loss of unconfined strength as the soil evolved from a CH toward a friction-dominated granular-like material. Because the highly heated soil was expected to derive a greater proportion of its strength from confinement-dependent frictional resistance, DST was also performed to provide a more representative assessment of its engineering shear behavior.

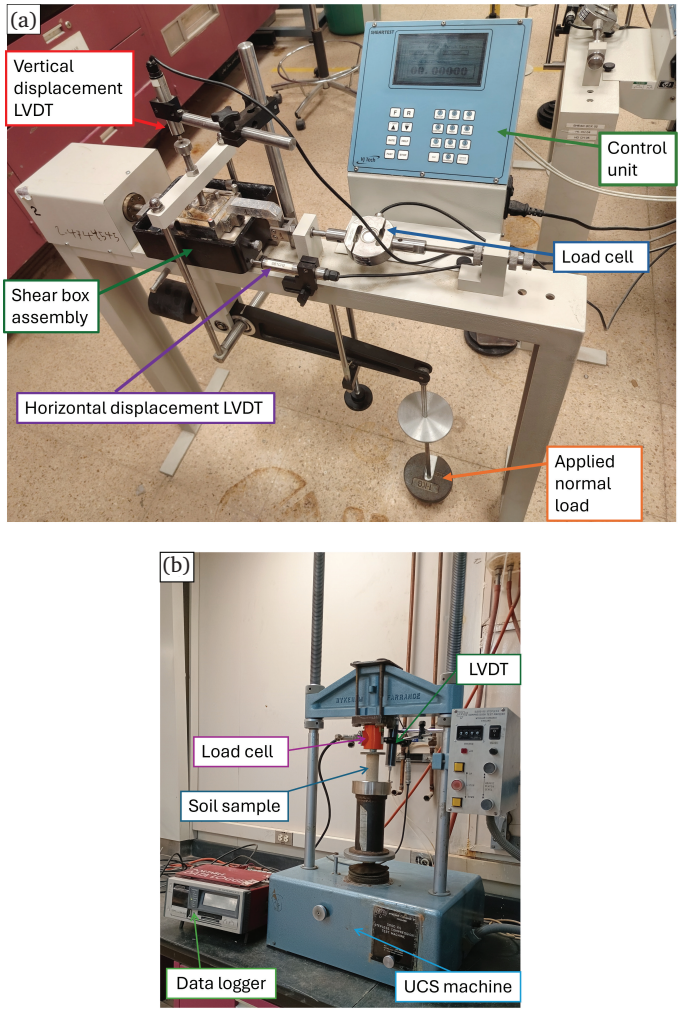


Fig. 1. Experimental apparatus used in the mechanical testing program: (a) direct shear test (DST) system and (b) unconfined compressive strength (UCS) testing machine.

Shear strength characteristics were determined through DST in accordance with ASTM D3080, with particular emphasis on quantifying cohesion (c) and the friction angle (φ). Tests were conducted using a shear box of 63.5 × 63.5 mm with a specimen thickness of 22.5 mm. The tests were performed under consolidated drained (CD) conditions using displacement control. For the untreated, 200°C, and 400°C conditions, DST were conducted under three normal stress levels of 50, 85, and 200 kPa. For the 600°C condition, additional normal stress levels of 40, 80, 120, 150, and 200 kPa were included to better characterize the response of the highly heated material and to assess the suitability of a linear Mohr–Coulomb failure envelope over the tested stress range. Horizontal shearing was applied under displacement control at a constant rate of 0.3 mm/min. Shearing was continued until a stable residual response was reached, corresponding to approximately 15% horizontal displacement. Peak shear stress was defined as the maximum shear stress recorded during the test. These peak values were then used to construct the Mohr–Coulomb failure envelopes and derive the shear strength parameters. Prior to horizontal shearing, each specimen was allowed to consolidate under the applied normal stress, and shearing was initiated only after the vertical deformation had essentially stabilized. The consolidation-stage deformation was monitored over a period extending to approximately 3 days, although the time required to approach stabilization varied with treatment condition and applied normal stress.

The number of specimens used in the present study was as follows. Grain-size distribution and compaction were each conducted as single determinations for every thermal condition because of the limited amount of soil available after heating. For consistency limits, the liquid limit (LL) was determined from a best-fit line constructed using six moisture-content measurements plotted against the logarithm of the corresponding number of blows for each condition, whereas the plastic limit (PL) and shrinkage limit (SL) were each determined from three repeated measurements. UCS was determined from duplicate specimens for each condition, and the results are reported as mean ± standard deviation. DST were conducted as single determinations at each applied normal stress level. For the 600°C condition, additional normal stress levels were included to better define the Mohr–Coulomb failure envelope; these additional data points are not replicate tests.

3. Results and Discussion

3.1 Granulometric transformation and textural evolution

Fig. 2 shows the grain size distribution curves for the untreated soil versus thermally treated samples at 200°C, 400°C, and 600°C for durations of 15, 30, and 120 minutes. Grain-size distribution was determined using a HORIBA Partica LA-950V2 laser scattering particle size analyzer under wet dispersion conditions. During testing, the suspension was maintained under continuous circulation and agitation before and during measurement, and ultrasonication was applied for 20 s immediately prior to measurement. No chemical dispersant was

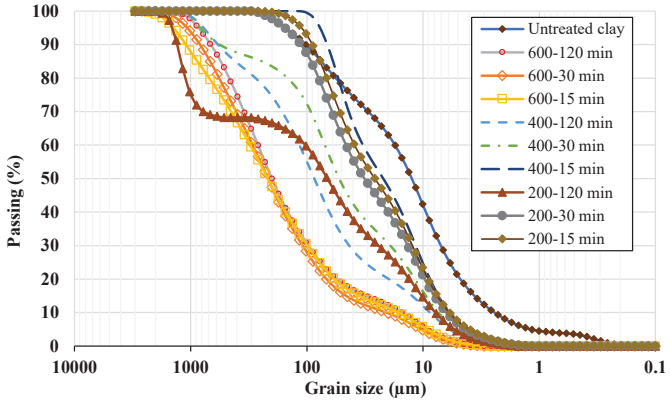


Fig. 2. Grain size distribution curves for the untreated soil versus thermally treated samples exposed to 200°C, 400°C, and 600°C for 15, 30, and 120 min.

Table 1.
Quantitative analysis of particle size distribution and geotechnical classification for untreated and thermally stabilized Al-Ghat clay.

Treatment temperature	Duration (min)	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	C_u	C_c	Fines (<75 μm) (%)
Untreated	--	0.0024	0.007	0.0125	0.0174	7.25	1.17	84.9
200°C	15	0.0059	0.0124	0.026	0.0388	6.58	0.67	83.9
	30	0.0063	0.0135	0.0319	0.046	7.3	0.63	78.0
	120	0.0078	0.0243	0.0667	0.1032	13.23	0.73	53.0
400°C	15	0.0059	0.0116	0.0221	0.0329	5.58	0.69	94.0
	30	0.0074	0.0192	0.0526	0.0701	9.47	0.71	62.5
	120	0.0087	0.0432	0.0863	0.1158	13.31	1.85	45.1
600°C	15	0.0163	0.099	0.2175	0.3075	18.87	1.96	24.3
	30	0.0208	0.1088	0.2163	0.2929	14.08	1.94	21.8
	120	0.0151	0.0969	0.1999	0.2625	17.38	2.37	24.8

Note: D_{10}, D_{30}, D_{50}, and D_{60} are the particle diameters corresponding to 10%, 30%, 50%, and 60% passing, respectively; C_u is the coefficient of uniformity, and C_c is the coefficient of curvature.

added, and no separate soaking stage was used. Therefore, the reported particle-size distributions represent the particle size retained after the adopted protocol.

Grain size distribution of Al-Ghat clay underwent a profound shift following thermal exposure, as quantified by the parameters in Table 1. In its natural state, the soil is characterized by a high fines content (84.9%) and a median particle size (D_{50}) of 0.0125 mm, typical of CH. However, thermal treatment at 400-600°C triggered a progressive aggregation of clay platelets into stable, sand-sized clusters. At 600°C, the D_{50} increased more than 15-fold to approximately 0.200 mm, while the fines content dropped drastically to 24.8%, shifting the USCS classification to Silty Sand (SM). Fig. 3 presents SEM observations revealing distinct microstructural differences between the untreated expansive soil and the soil subjected to thermal treatment at 600°C.

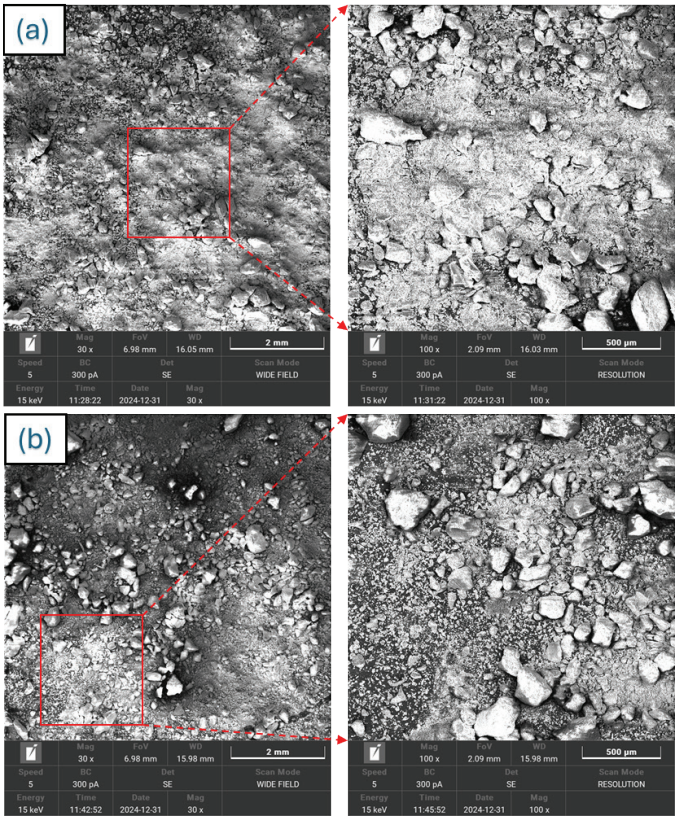


Fig. 3. SEM micrographs of the soil at magnifications of 30x (left) and 100x (right): (a) untreated expansive soil and (b) soil thermally treated at 600°C for 2 h (Alsabhan *et al.*, 2025).

This textural evolution is consistent with the mineralogical and microstructural changes previously reported for the same Al-Ghat clay by Alsabhan *et al.* (2025), who associated heating at 600°C with kaolinite dehydroxylation and agglomeration of particles into coarser fused structures. Interestingly, the data in Table 1 reveals that at 400°C, the transformation is highly duration-dependent; extending the exposure from 15 to 120 minutes reduced the fines from 94.0% to 45.1%. This suggests that the kinetic energy required for particle cementation at intermediate temperatures necessitates a prolonged retention time, whereas the stabilization at 600°C appears nearly instantaneous.

3.2 Modifications in consistency and state parameters

Fig. 4 shows the Atterberg limits of untreated and thermally treated expansive soil at different heating temperatures. The transition from plastic clay to a granular-like material is further evidenced by the sharp reduction in Atterberg limits. Exposure to 600 °C lowered the PI from 27.0 in the untreated condition to 2.94, signifying a transition to an essentially non-plastic soil. This behavior aligns with the findings of Kabubo *et al.* (2017), who observed that heating black cotton soil to 600°C resulted in a complete loss of plasticity.

For clarity, the LL values reported in this study were obtained from a best-fit line constructed using six moisture-content measurements plotted against the logarithm of the corresponding number of blows for each condition, whereas the PL and SL values are reported as mean ± standard deviation based on three repeated measurements. The PL values were 40.88 ± 1.64%, 38.78 ± 1.30%, and 32.02 ± 0.18% for the 200, 400, and 600°C conditions, respectively. The corresponding values were 23.39 ± 0.46%, 32.74 ± 1.43%, and 30.24 ± 2.74%.

While the reduction in plasticity is often discussed in terms of swelling mitigation, its impact on structural strength is paramount. The elimination of the adsorbed water layer around clay particles allows

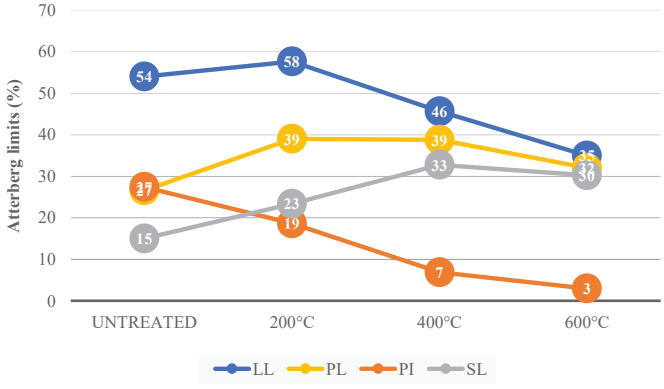


Fig. 4. Atterberg limits results (LL, PL, PI, and SL) of untreated and thermally treated expansive soil exposed to 200, 400, and 600°C.

Table 2.
Compaction parameters (MDD and OMC) for the expansive soil under various thermal conditions.

Soil sample	Temperature (°C)	Duration (min)	MDD (g/cm³)	OMC (%)
Natural soil	--	--	1.63	25
200_120 min	200	120	1.6	25.5
400_15 min	400	15	1.52	24.3
400_30 min	400	30	1.525	24.1
400_120 min	400	120	1.493	26.5
600_15 min	600	15	1.465	26.5
600_30 min	600	30	1.46	25.8
600_120 min	600	120	1.38	27.5

Note: MDD = Maximum dry density; OMC = Optimum moisture content.

for closer, direct contact between grains. As shown in Table 1, the Coefficient of Uniformity (C_u) increased from 7.25 (untreated) to 17.38 (600°C- 120 min), indicating the development of a more well-graded skeleton. This expanded range of grain sizes facilitates denser packing and enhanced mechanical interlocking, which are critical for sustaining engineering loads without the risk of plastic deformation.

3.3 Compaction characteristics

The compaction behavior of expansive soil is a critical indicator of its suitability for engineering fill and subgrade applications. As established in the experimental protocols, the mini-compaction method was employed to derive the MDD and OMC. Table 2 shows the compaction parameters (MDD and OMC) for the expansive soil under various thermal conditions. Testing revealed that the soil in its natural state compacted to a MDD of 1.63 g/cm³ when the moisture content was near 25%.

3.3.1 Impact of temperature on density and moisture

Thermal treatment initiated a distinct degradation in the soil's compactability. At 200°C for 120 minutes, the MDD decreased slightly to 1.60 g/cm³, while the OMC increased to 25.5%. This modest change suggests that while hygroscopic water is removed, the primary soil fabric remains largely intact at this temperature. However, as the temperature increased to 400°C and 600°C, a more pronounced reduction in MDD was observed. For the 120-minute duration, the MDD dropped to 1.493 g/cm³ at 400°C and further to its lowest value of 1.38 g/cm³ at 600°C. This progressive decline in density is consistent with the pronounced coarsening and structural alteration observed after heating, and with the mineralogical/microstructural changes previously reported for the same soil in Alsabhan *et al.* (2025). These thermally induced structures are more resistant to mechanical packing, leading to the flattening of compaction curves and a loss in compaction efficiency as noted in previous studies (Alsabhan *et al.*, 2025; Alsabhan and Hamid, 2025; Iriarte *et al.*, 2025; Mañosa *et al.*, 2023).

3.3.2 Influence of heating duration

The data revealed that the duration of heating significantly influences the degree of structural modification, particularly at higher temperatures. At 400°C, reducing the heating time from 120 minutes to 15 minutes resulted in a higher MDD (1.52 g/cm³) and lower OMC (24.3%). A similar trend was observed at 600°C, where the MDD increased from 1.38 g/cm³ (120 min) to 1.465 g/cm³ (15 min).

These results indicate that the transformation of clay minerals into stable, coarser aggregates is a time-dependent process. Shorter durations may not allow for the complete breakdown of the crystalline lattice, leaving a portion of the soil in a more compactable state. Conversely, the 120-minute exposure at high temperature likely represents a more advanced stage of thermal alteration, as suggested by the stronger changes in gradation and compaction behavior.

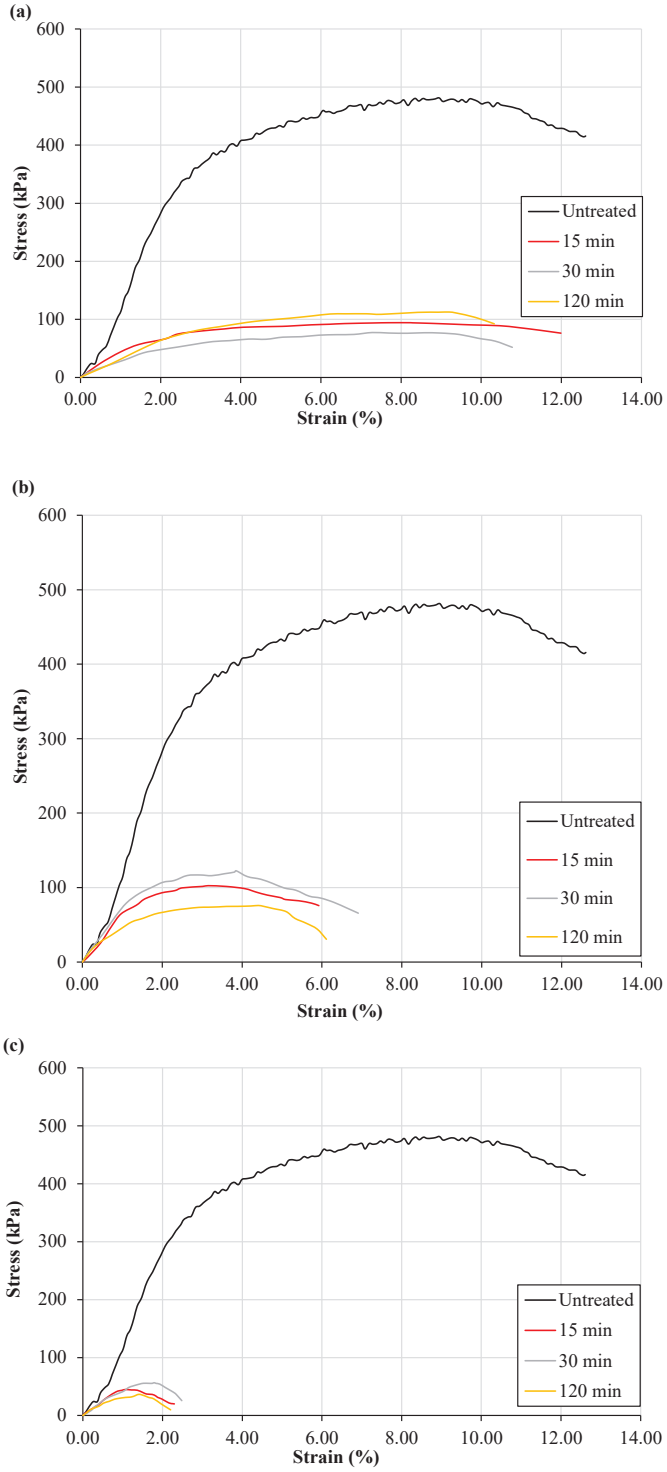


Fig. 5. Stress-strain relationships for treated expansive soil at different treatment durations and different heating temperatures; (a) 200°C, (b) 400°C, and (c) 600°C.

3.4 UCS characteristics

Fig. 5 presents the stress–strain curves of the thermally treated expansive soil at various heating temperatures and duration conditions. Fig. 6 provides a consolidated summary of the UCS results for both the untreated soil and the samples subjected to thermal treatment. The values shown in Fig. 6 represent the mean UCS of duplicate specimens for each treatment condition, and the error bars indicate ± one standard deviation. The experimental results demonstrate that extreme thermal treatment leads to a substantial and progressive reduction in the UCS of

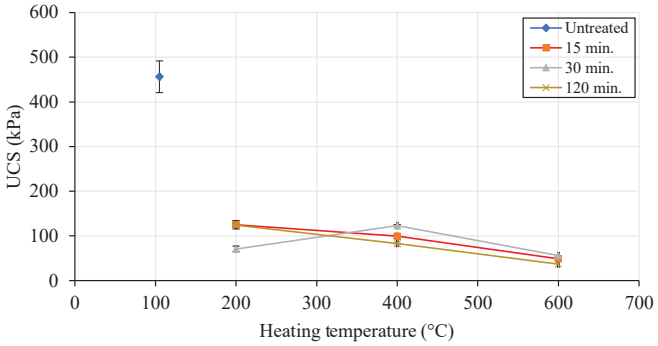


Fig. 6. UCS results of untreated and thermally treated expansive clay, presented as mean values with ± standard deviation based on duplicate specimens.

the expansive clay, a trend that is intimately linked to the fundamental changes observed in the soil's physical and index properties. In its natural, untreated state, the soil exhibits a relatively high compressive resistance of approximately 430 kPa. This high initial strength is a direct result of the soil's CH matrix (PI = 27.0) and high fines content (84.9%), which provide significant inter-particle cohesion and a dense, compactable fabric with a MDD of 1.628 g/cm³.

Subjecting the soil to 200°C results in a sharp initial drop in UCS to a range of 70–125 kPa. At this temperature, the stress-strain curves maintain a ductile failure mode, with the 120-minute treatment yielding a peak stress of 124 kPa. This reduction in strength correlates with the initial changes in consistency and compaction; the MDD begins to decrease slightly to 1.60 g/cm³, and the particle size median (D_{50}) starts to shift from 0.0125 mm toward coarser aggregates. The removal of hygroscopic moisture at this stage weakens the surface tension forces between clay platelets, leading to an immediate loss in unconfined stability.

As the treatment temperature reaches 400°C, the UCS remains suppressed within a range of 83–123 kPa. This mechanical plateau is a direct reflection of the transitional state of the soil's mineralogy. While the dehydroxylation of kaolinite has commenced, the soil still retains a significant fine fraction (45.1% after 120 minutes) and a PI of approximately 7.00. The MDD further declines to 1.493 g/cm³, indicating a less efficient packing of the evolving granular skeleton. Stress-strain behavior at this threshold begins to show a decrease in strain at failure, moving away from the ductile response of lower temperatures toward a more brittle failure.

The most severe reduction in compressive strength occurs at 600°C, where the UCS reaches its lowest recorded levels of 37–56 kPa. This precipitous drop is explained by the near-complete transformation of the soil into a non-plastic (PI = 3.00), well-graded SM. The D_{50} increased 16-fold to 0.1999 mm, and the fines content dropped to just 24.8%, confirming that the cohesive clay matrix has been replaced by a granular aggregate skeleton. Because the thermally treated soil progressively lost its clay-bonded structure and became increasingly granular, the substantial reduction in UCS, together with the reduction in MDD to 1.38 g/cm³, indicates that the material cannot sustain significant axial loads without confinement. At the same time, the present results indicate an important limitation in interpreting UCS for the highest treatment level. As the soil becomes less plastic and more granular, unconfined compression no longer captures the principal strength mechanism governing field performance, because the material increasingly relies on confinement-dependent friction rather than cohesive bonding. Accordingly, UCS is interpreted here mainly as a measure of the loss of unconfined structural integrity during thermal treatment, whereas the direct shear results provide the more relevant basis for assessing the engineering performance of the highly heated material in confined applications.

The evolution of UCS provides macroscopic validation of microscopic and index property changes. The transition from a ductile, 456 kPa clay to a brittle, 37 kPa sand-like aggregate (after 120 min at 600°C) is mechanically consistent with the strong changes in gradation, plasticity, density, and cohesion observed after heating, and with the microstructural/mineralogical alterations previously reported for the same soil (Alsabhan *et al.*, 2025). While these results confirm that extreme heating compromises unconfined strength, the corresponding massive gain in the internal friction angle to 50.19° suggests that the stabilized Al-Ghat clay is a high-performance material for structural fill applications where lateral confinement is provided.

From an engineering implementation perspective, thermal stabilization may be applied either in situ, through localized heating methods such as borehole combustion or electric heating systems, or ex situ, by treating excavated soil in a controlled facility prior to reuse. For extreme treatment levels such as 600°C, the ex-situ route is likely to be more practical because it allows better control of temperature distribution, exposure duration, and treatment uniformity. At the same time, several limitations must be recognized, including the high energy demand associated with extreme heating, the difficulty of achieving uniform treatment in heterogeneous field deposits, and the need for further validation of long-term large-scale performance. In view of the present results, the principal engineering value of such treatment lies in converting expansive clay into a non-expansive frictional material suitable for confined applications, such as engineered fills, embankments, and pavement subgrades, rather than for applications in which unconfined compressive resistance governs design. This interpretation is consistent with earlier observations reported by Abu-Zreig *et al.* (2001), who showed that severe heating can markedly reduce the unconfined strength of clayey soils through irreversible disruption of inter-particle bonding.

3.5 Shear strength parameters

3.5.1 Swell potential mitigation

The inherent expansiveness of the clay soil and its response to thermal conditioning are quantified in Fig. 7. In its untreated state, the soil exhibits a high free swell potential of approximately 7.0%, which is directly attributable to its high-PI (PI = 27.0) and high fines content (84.9%). Thermal treatment initiates a progressive and marked reduction in this behavior; at 200°C, the free swell is halved to 3.0%, and at 400°C, it further declines to roughly 2.0%. Most notably, treatment at 600°C effectively eliminates the soil's expansive nature, with free swell values reaching nearly 0%. This stabilization represents a fundamental mineralogical shift, as the dehydroxylation of kaolinite into metakaolin destroys the layered crystalline structure and eliminates the primary mechanism for water adsorption and lattice expansion.

The progressive reduction in free swell observed in this study is consistent with prior experimental evidence reported by Alsabhan *et al.* (2025) for thermally treated expansive soils, based on oedometer consolidation tests. Their results showed a reduction in free swell from approximately 6–7% in the untreated state to about 3% at 200°C, decreasing further to around 2% at 400°C, and becoming nearly zero following treatment at 600°C. Similar near-complete elimination of swelling and swelling pressure at 600°C has been widely reported for kaolinitic and mixed-clay expansive soils, irrespective of whether conventional furnace heating or alternative thermal techniques were

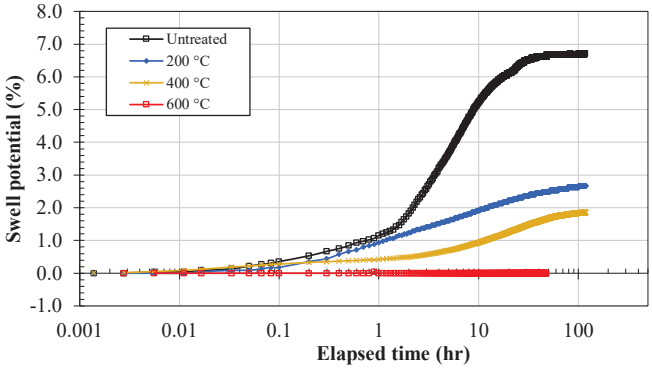


Fig. 7. Comparison of the free swell potential for Al-Ghat expansive soil in its natural (untreated) and thermally treated states. (200°C, 400°C, and 600°C).

employed (Kabubo *et al.*, 2017, 2015; Tamiru *et al.*, 2025; Wang *et al.*, 2008; Yao *et al.*, 2022). For example, Wang *et al.* (2008) and Kabubo *et al.* (2017) demonstrated that heating expansive clays to 600°C is sufficient to render them effectively non-expansive, while Tamiru *et al.* (2025) identified 400°C as a critical threshold for significant improvement and reported non-plastic behavior and elimination of swelling pressure at 600°C. Furthermore, Yao *et al.* (2022) reported that such thermal exposure induces a transition toward a non-cohesive soil structure and the development of a coarser, more stable soil fabric. Collectively, these comparisons confirm that the thermal decomposition of kaolinite into metakaolin constitutes a permanent and highly reliable ground improvement mechanism for expansive soils.

3.5.2 Consolidation behavior and structural stiffness

The initial mechanical response under vertical confinement is illustrated in Fig. 8, depicting specimen height changes under vertical stresses of 50, 85, and 200 kPa. The untreated and 200°C specimens exhibit typical primary consolidation curves, where substantial vertical compression occurs as the clay matrix rearranges and moisture is expelled. This high compressibility correlates with the high fines content and relatively low initial particle size (D_{50} = 0.0125 mm). Conversely, specimens subjected to 600°C display a marked reduction in vertical deformation during the consolidation phase. This increased stiffness is a mechanical manifestation of the textural evolution documented in Table 1; the aggregation of fine clay into stable, sand-sized clusters (D_{50} = 0.1999 mm) creates a rigid internal skeleton. While the MDD decreased from 1.628 g/cm³ (untreated) to 1.380 g/cm³ (600°C_120 min), these thermally fused aggregates are inherently more robust and resistant to settlement than the original cohesive fabric. This reduced consolidation-stage deformation at 600°C is consistent with the later dilative and peak-dominated shear response observed during shearing, whereas the greater consolidation compression of the untreated and lower-temperature specimens is consistent with their more contractive behavior.

3.5.3 Volumetric response and dilatancy

Fig. 9 presents the vertical deformation versus horizontal displacement during shearing. The untreated soil and specimens treated up to 400°C demonstrate predominantly contractive behavior, characteristic of fine-grained soils where particles are forced into a denser configuration during shear. A fundamental behavioral shift occurs at 600°C, where the soil exhibits clear dilatant behavior (volume increase) under low normal stress (50 kPa). This dilatation is a direct consequence of the "sanding" of the clay; the large, irregular aggregates must physically lift over one another to facilitate shear displacement. This transition from contractancy to dilatancy confirms that the material now behaves as a well-graded granular medium (C_u increased from 7.20 to 17.38), moving away from the plastic deformation mechanisms of cohesive clay.

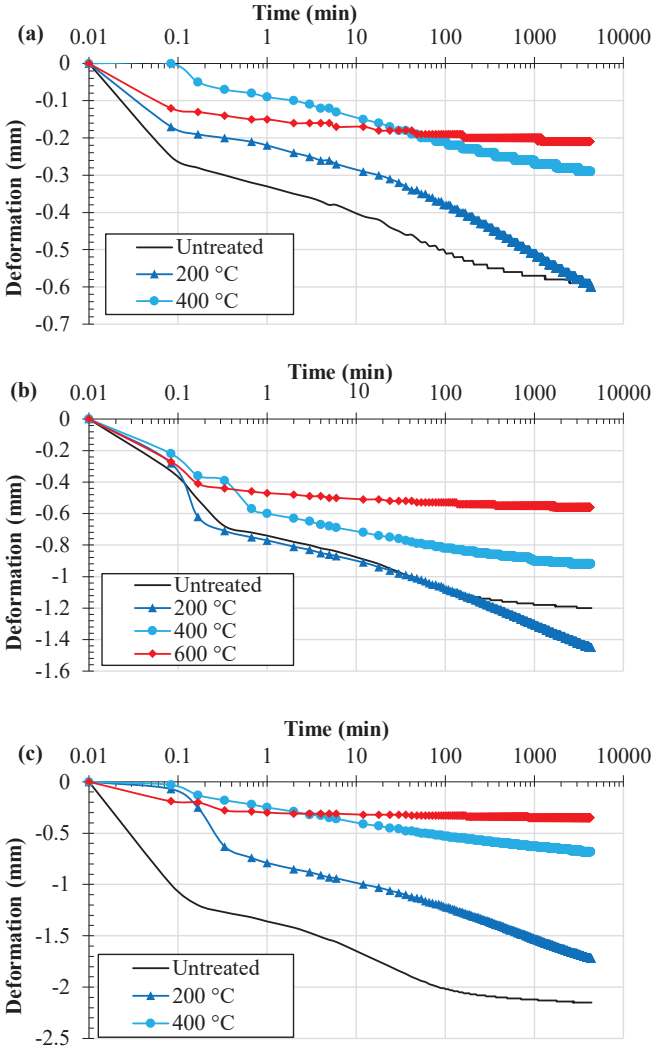


Fig. 8. Consolidation behavior (specimen height change vs. time) for untreated and thermally treated specimens under vertical stress increments: (a) low stress 50 kPa, (b) moderate stress 85 kPa, and (c) high stress 200 kPa.

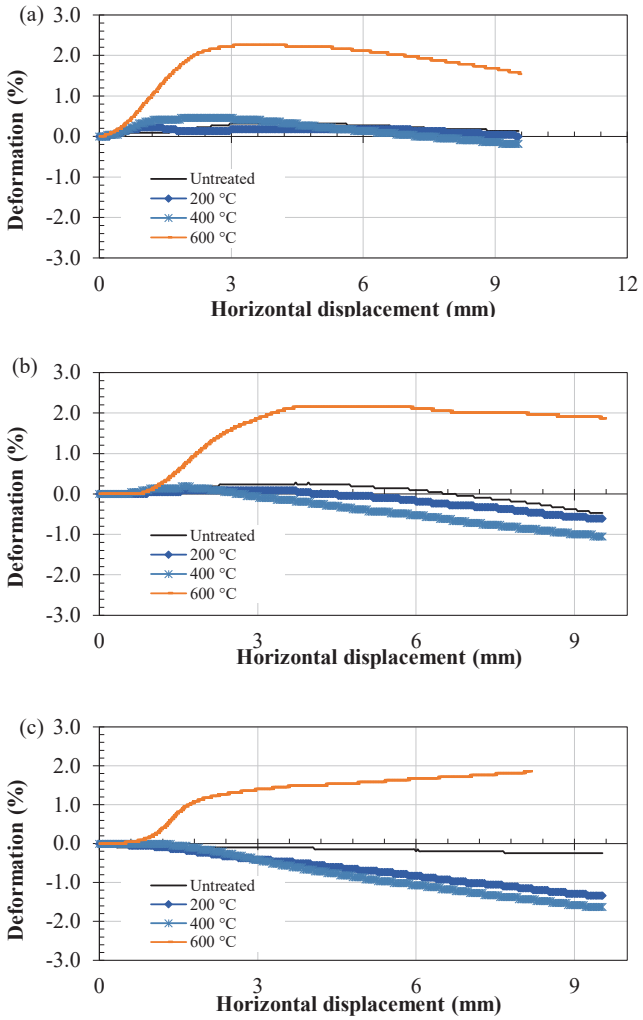


Fig. 9. Volumetric response (vertical deformation vs. horizontal displacement) during the shearing phase for specimens subjected to varying thermal treatments under (a) 50 kPa, (b) 85 kPa, and (c) 200 kPa normal stresses.

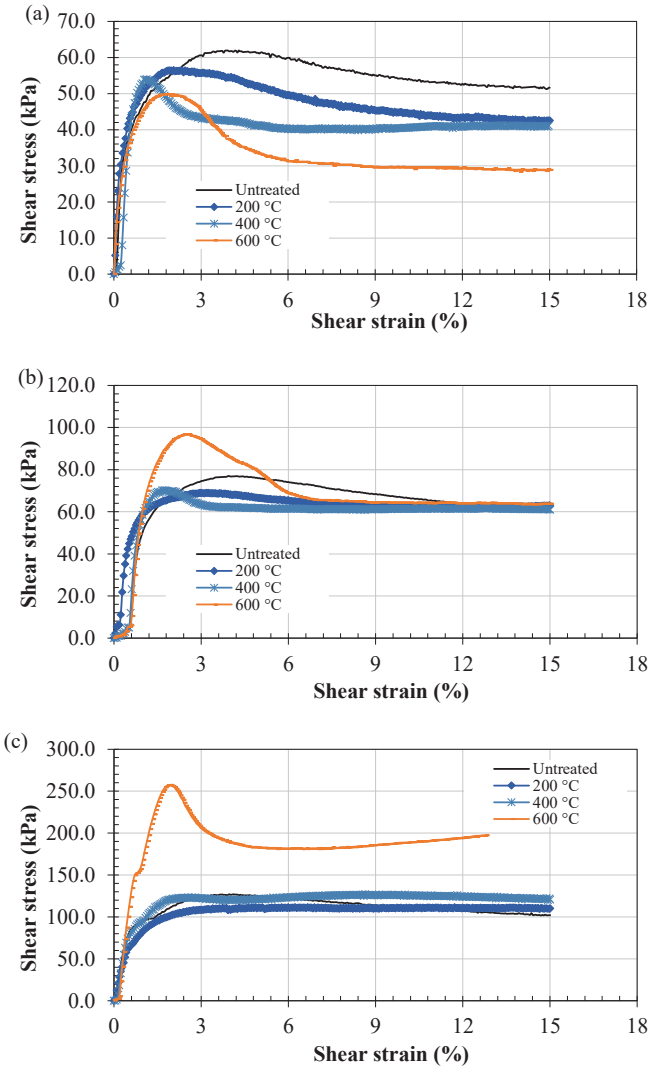


Fig. 10. Shear stress versus shear strain for untreated and thermally treated soil specimens under normal stresses: (a) low stress 50 kPa, (b) moderate stress 85 kPa, and (c) high stress 200 kPa.

3.5.4 Shearing resistance and peak strength mobilization

The relationship between shear stress and horizontal displacement is elucidated in Fig. 10. The untreated soil follows a ductile, strain-hardening path, where shear resistance increases gradually without a well-defined peak. This correlates with the ductile failure mode and high axial strains (8–10%) observed in the low-temperature UCS tests (Fig. 4(a)). In contrast, the 600°C specimens develop a sharp peak shear stress followed by strain-softening behavior. Under high confinement (200 kPa), the shear resistance of the 600°C soil significantly exceeds that of the untreated state. This indicates that while the material becomes brittle; consistent with the low failure strains (< 2.5%) seen in the 600°C UCS curves; the formation of a sintered granular fabric allows for the mobilization of immense shear resistance through mechanical interlocking and aggregate friction.

3.5.5 Evolution of Mohr–coulomb parameters

The failure envelopes in Fig. 11 and the parameters in Table 3 quantify a profound trade-off between the cohesive and frictional components of strength. Cohesion (c) experienced a precipitous decline, dropping from 40.89 kPa in its untreated state to just 5.28 kPa at 600°C. This 87% reduction in cohesive behavior is the primary cause for the dramatic 92% loss in unconfined strength, as UCS dropped from approximately 456 kPa to 37 kPa. The destruction of electrochemical

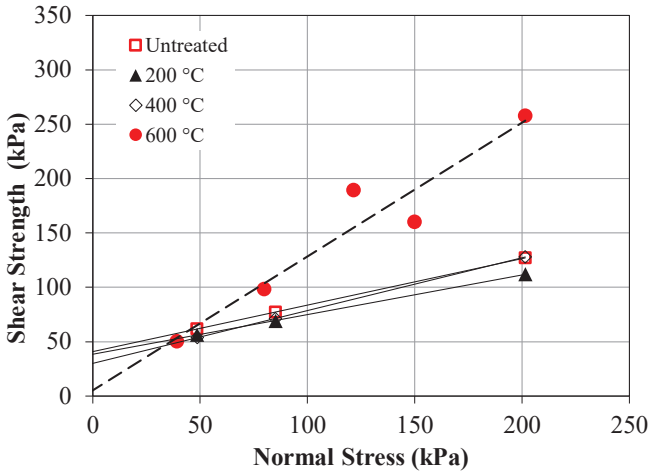


Fig. 11. Mohr–Coulomb failure envelopes for untreated and thermally treated expansive clay specimens exposed to 200°C, 400°C, and 600°C.

Table 3.
Shear strength parameters and failure envelope equations derived from DSTs at varying treatment temperatures.

Treatment temperature	Cohesion, c (kPa)	Internal friction angle, φ (°)	Failure envelope equation	Coefficient of determination (R^2)
Untreated	40.89	23.15	$\tau = 0.42\sigma + 40.886$	0.9999
200°C	38.47	19.8	$\tau = 0.36\sigma + 38.469$	0.9998
400°C	30.07	25.64	$\tau = 0.48\sigma + 30.072$	0.9999
600°C	5.28	50.19	$\tau = 1.2\sigma + 5.281$	0.9177

bonds during dehydroxylation effectively eliminates the forces that sustain unconfined axial loads (Gray, 1970).

Conversely, the angle of internal friction (φ) increased from 23.15° in the untreated state to a remarkable 50.19° at 600°C. The high peak friction angle at 600°C is interpreted as the combined result of aggregate interlocking, confinement-dependent peak resistance, and dilation during shearing in the thermally altered granular-like skeleton. These results align with previous research, which observed that extreme heating transforms expansive clays into robust, non-cohesive granular mediums (Kabubo *et al.*, 2017; Yao *et al.*, 2022). Taken together, these results indicate that while thermal stabilization sacrifices cohesive strength (UCS), it can produce a granular-like frictional material with high peak shear resistance under confinement. However, the reported value should be interpreted as a peak friction angle obtained from the present CD direct shear configuration and tested stress range. Because the DST were conducted as single determinations at each normal stress level, the exact numerical value should be interpreted cautiously and not as a fully replicated material constant.

This shift in shear strength mechanisms is fundamentally supported by the evolution of the soil's gradation characteristics. As treatment temperatures reached 600°C, the C_u increased from 7.20 to a significant 17.38. This jump in C_u represents a transition from a relatively uniform clayey material to a highly well-graded granular medium, as the thermal fusion of clay platelets produces a wide spectrum of stable aggregate sizes (as seen in Fig. 3). From a microstructural standpoint, this improved gradation allows for a more efficient packing arrangement where smaller silt-sized clusters fill the voids between larger, sand-sized aggregates, creating a dense and interlocking soil skeleton. This enhanced mechanical interlocking is the primary driver behind the remarkable friction angle of 50.19°, as the well-graded nature of the metakaolin clusters necessitates significantly higher energy to overcome particle interference and rotation during shearing (Ahmed *et al.*, 2023; Guo *et al.*, 2023). Consequently, the C_u value serves as a critical bridge linking the physical "sanding" of the clay observed in granulometric tests to the superior frictional performance quantified in the direct shear results.

4. Field implementation and environmental challenges

Even though controlled heating has proven effective in the laboratory for stabilizing expansive clay, implementing this approach in real-world projects faces considerable challenges related to cost, feasibility, and environmental impact. This section synthesizes the critical challenges identified in recent research to provide a realistic framework for the future adoption of thermal ground improvement.

4.1 Technical and practical implementation challenges

The primary technical obstacle in field implementation is the inherent heterogeneity of natural soil deposits. Non-uniform heating often arises because moisture levels, density conditions, and mineralogical characteristics differ from one location in the soil deposit to another. This non-uniformity may lead to inconsistent stabilization across the treatment volume and generate tensile stresses that cause thermal cracking, potentially compromising the overall structural integrity of the improved zone (Alsabhan and Hamid, 2025; Heidari *et al.*, 2025; Loria and Coulibaly, 2021).

Furthermore, achieving effective treatment at depth remains a formidable engineering constraint. Because microwave energy attenuates quickly in soil, its practical influence is generally confined to the upper 20 cm of the profile (Bondarenko and Boshkova, 2023; Hu *et al.*, 2023; Jastrzębska, 2019; Yao *et al.*, 2022; Zhang *et al.*, 2025). Logistically, maintaining consistent temperatures, ensuring uniform heat distribution (e.g., through optimized borehole spacing), and managing post-treatment cooling are complex tasks requiring specialized equipment and expertise that are not yet standard in the construction industry.

4.2 Economic and environmental considerations

The high energy intensity required to reach the stabilization thresholds of 400°C to 600°C remains a major barrier to commercial viability. Thermal stabilization incurs substantial energy costs that may not be economically competitive with traditional methods like lime treatment or soil replacement in regions with high energy prices or limited resources (Alsabhan and Hamid, 2025; Ding *et al.*, 2019; Ren *et al.*, 2020).

From an environmental perspective, large-scale heating relying on fossil fuels can result in significant greenhouse gas emissions. However, as the previous studies notes, microwave heating offers a potentially cleaner alternative with reduced direct emissions if powered by sustainable sources (Yao *et al.*, 2022; Zhang *et al.*, 2024). Furthermore, the use of these high-energy techniques in environmentally fragile areas also raises social acceptability concerns, which should be assessed through comprehensive Life-Cycle Assessments (LCA) evaluations (Benghazi *et al.*, 2024; da Rocha *et al.*, 2016).

4.3 Long-Term performance and future directions

A significant uncertainty that remains is how thermally treated soils behave over extended periods under variable and fluctuating environmental influences. There are lingering concerns regarding the potential reversal of stabilized soil properties over time in response to seasonal temperature cycles and groundwater fluctuations (Heidari *et al.*, 2025; O'Brien *et al.*, 2018).

Given these in-situ challenges, a more immediately feasible approach is the ex-situ treatment of excavated expansive soils at dedicated, controlled facilities. This allows for superior quality control and uniform mineralogical transformation. Future research should prioritize the development of more energy-efficient heating systems, the optimization of hybrid stabilization approaches (e.g., combining thermal and chemical methods), and the execution of long-term field trials to validate the permanence of the achieved improvements under real-world loading and climatic conditions.

5. Conclusions

This study examined the effects of extreme thermal treatment on the mechanical and volumetric behavior of a kaolinite-rich expansive clay through a comprehensive experimental program incorporating UCS, DST, and supporting index and granulometric analyses. Based on the results obtained, the following conclusions can be drawn:

Thermal treatment fundamentally alters soil fabric and classification. Heating at temperatures of 400–600°C induced irreversible aggregation of clay platelets into stable, sand-sized clusters, increasing the median particle size (D_{50}) by more than an order of magnitude and reducing fines content from 84.9% to approximately 25%. As a result, the soil transitioned from a CH to a well-graded silty sand (SM). Expansive behavior is permanently mitigated at elevated temperatures. Free swell potential decreased progressively with temperature and was effectively eliminated at 600°C. This improvement is attributed to the dehydroxylation of kaolinite and its transformation into amorphous metakaolin, which destroys the layered mineral structure responsible for water adsorption and swelling. Extreme heating causes a pronounced reduction in unconfined compressive strength. The UCS decreased from approximately 430 kPa in the untreated soil to as low as 37 kPa after treatment at 600°C. This reduction reflects the loss of electrochemical bonding and cohesive forces within the clay matrix, confirming that unconfined strength is not an appropriate performance indicator for thermally stabilized soils at high temperatures. Shear strength under confinement is significantly enhanced. Despite the loss of cohesion, the angle of internal friction increased markedly with temperature, reaching 50.19° at 600°C. This enhancement is driven by the formation of rough, interlocking metakaolin aggregates and improved gradation, which promote mechanical interlocking and frictional resistance during shearing. Thermal stabilization transforms the soil's load-bearing behavior from ductile, cohesion-controlled deformation to brittle, friction-controlled response. Consequently, thermally treated expansive clay exhibits superior performance under confined conditions, making it well suited for applications such as engineered fills, embankments, and pavement subgrades. While extreme heating is not suitable where unconfined compressive resistance is required, it produces a stable, non-expansive granular-like material with high peak shear resistance under confinement. These findings support the use of thermal stabilization as a viable ground improvement technique when design conditions provide lateral restraint. Overall, this research demonstrates that extreme thermal treatment offers a reliable means of converting problematic expansive clay into a high-performance frictional material. The results provide a mechanistic framework linking mineralogical transformation, fabric evolution, and strength behavior, thereby supporting informed adoption of thermal stabilization in geotechnical engineering practice.

CRediT authorship contribution statement

Abdullah Alsabhan: Conceptualization, methodology, resources, supervision, funding acquisition, project administration, writing – review & editing. **Wagdi Hamid:** Methodology, formal analysis, investigation, data curation, writing – original draft preparation, writing – review & editing. **Ahmed M. Al-Mahbashi:** Conceptualization, methodology, formal analysis, investigation, data curation, writing – review & editing. Authors read and agreed to the published version of the manuscript.

Declaration of competing interest

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.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Large Language Models in order to assist in drafting and refining the language for clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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