Temperature Induced Variations in Soil Shear Strength: Experimental Approach

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Abstract

This study examines the effect of elevated temperatures on the shear strength behaviour of soil within the range of 27 to 600 °C. Experimental work comprised of index property characterization, Standard Proctor compaction, direct shear testing and California Bearing Ratio (CBR) assessment. The results show that moderate heating (110–200 °C) leads to a marginal increase in cohesion, attributed to partial dehydration of clay minerals and enhanced particle interlocking. Beyond 300 °C, pronounced structural degradation occurs, resulting in a steep reduction in cohesion from 60 kN/m² at untreated to complete loss at 500 °C. Conversely, the internal friction angle increases progressively from 17° to 47° at 600 °C, indicating a shift from cohesive behaviour to a friction dominated granular response. Overall, the soil exhibits a 72% reduction in shear strength at 600 °C. Microstructural and mineralogical transformations identified through XRD, SEM and EDS corroborate these mechanical changes. The findings highlight the non-linear thermal sensitivity of soil and provide critical insights for geotechnical design in high-temperature scenarios, including fire-affected foundations, geothermal infrastructure and thermal waste containment systems.

Keywords: clay, shear strength, CBR, thermal treatment

1. Introduction

Temperature is a key environmental factor that can significantly modify the engineering behaviour of soils, influencing hydraulic, mechanical and physico-chemical properties (Paaswell, 1973). Earlier studies have shown that clayey soils undergo noticeable shifts in permeability, strength and volume change when subjected to thermal variations. With the continuous expansion of subsurface infrastructure such as high-voltage transmission cables, buried oil and gas pipelines and deep geological waste repositories. The interaction between soil and heat has become an increasingly important topic in both geotechnical and geoenvironmental engineering. Soils surrounding these facilities are frequently exposed to elevated temperatures for prolonged durations, which may alter their performance by affecting mineral structure, suction, consolidation behaviour and shear strength.

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Natural and engineered heat sources can expose soils to high temperatures. These include wildfire events, geothermal activity, industrial heat discharge and thermal remediation processes. Such heating can alter basic soil properties, including Atterberg limits, compaction behaviour and shear strength. Early investigations by Hogentogler (1929)demonstrated that rising temperature reduces optimum moisture content and increases maximum dry density of clayey soils, emphasising temperature related structural rearrangement. Atterberg limits have long been linked to clay behaviour and temperature sensitivity of liquid and plastic limits has been used to evaluate soil consistency and chemical compatibility, especially for clays employed in barrier or containment systems. Several subsequent studies have supported the view that elevated temperatures influence consolidation behaviour, generally reducing preconsolidation pressure and modifying compressibility characteristics (Towhata, 2008 and Villar, 2005).

Thermal effects on shear strength have also been widely reported. Abuel-Naga et. al.(2012) highlighted that changes in shear strength of clays at high temperature are closely related to thermally induced volume changes. Other studies have demonstrated that the friction angle may either increase, decrease or remain unchanged depending on mineralogy, clay type and stress history. Heating can also drive mineral dehydration, lead to evaporation of pore and adsorbed water and cause microstructural rearrangement, all of which collectively influence the mechanical response of soils. Temperature induced variations in particle size distribution have been observed, with sandy soils tending to lose finer fractions and clayey soils showing aggregation, increased fine content due to thermal bonding(Bhatnagar 2002).

Hydraulic behaviour is likewise affected by temperature. For bentonite and other expansive clays, hydraulic conductivity varies primarily due to temperature-dependent changes in water viscosity and density. Studies by Towhata(1993), Villar (2009) confirmed that the permeability response under heating. Additionally, cation exchange capacity (CEC), a parameter associated with clay mineral behaviour and surface chemistry, has been shown to reduce significantly beyond 100 °C, further affecting soil strength and consistency.

Microscale analyses, such as X-ray computed tomography (CT) and field emission scanning electron microscopy (FESEM), have proven valuable in complementing laboratory-scale mechanical tests by providing direct evidence of fabric alteration, pore restructuring and particle bonding under thermal loading. Although several studies have explored temperature effects up to 120 °C, 150 °C and even 400 °C, research extending into higher temperature ranges remains limited. Moreover, microscale understanding of soil degradation under elevated temperature is still incomplete, particularly for clayey soils subjected to extreme heating (Cho, 2001).

In view of these gaps, the present study focuses on experimentally evaluating the influence of elevated temperatures on the shear strength parameters such as cohesion (c) and friction angle (ϕ) of soil over a wide temperature range from 27 °C to 600 °C. By integrating controlled heating with direct shear testing, the study aims to clarify the thermo-mechanical transitions that occur at higher temperatures. These changes are studied with microstructural analysis with SEM and XRD. The findings contribute to improved prediction of soil performance in high-temperature environments associated with fire exposure, thermal waste containment, geoenergy systems and underground infrastructure.

2.Materials and methodology

2.1 Soil

The soil used in this study was collected from a depth of 1.0 m representative of natural conditions. The sample was air dried, pulverized for further treatment. The soil is named as DBSK (Dark Brown Soil Kudair) collected from Kudair, Anantapur District, Andhra Pradesh bearing coordinates 14.733763^0, 77.457013^0. table shows basic and index properties of DBSK soil.

2.2 Thermal treatment Procedure

Thermal treatment was performed using a controlled muffle furnace. Each specimen was placed inside the furnace and heated to the designated temperature at a uniform rate of 5°C/min. The target temperature was maintained for a duration of 180 minutes to ensure uniform thermal penetration throughout the specimen. Each soil sample is thermally treated at 110, 200, 300, 400, 500, 600°C. After heating, samples were allowed to cool naturally to room temperature to avoid thermal shock.

Table 1: basic and index properties of DBSK soil

Property	DBSK
Natural Moisture content	5.3
Liquid limit (%)	74.8
Plastic limit(%)	31.7
Plasticity index	43.1
Specific gravity	2.71
ISSCS classification symbol	CH
Maximum dry density (g/cc)	1.48
Optimum moisture content (w_{opt}) (%)	13
Gravel (>4.75 mm)	0
Sand (4.75 mm – 75 µm) (%)	0
Silt (75 µm – 2 µm) (%)	72
Clay (< 2 µm) (%)	28

2.3 Testing methodology

Preliminary characterization of the soil involved particle size distribution (IS 2720 Part 4), Atterberg limits (IS 2720 Part 5), and Standard Proctor compaction (IS 2720 Part 7) to determine the maximum dry density (MDD) and optimum moisture content (OMC). These index properties served as the baseline for evaluating subsequent changes induced under various thermal exposure conditions. The soil was then compacted at its MDD and OMC to prepare uniform specimens for direct shear testing in accordance with IS 2720 Part 13, with a minimum of three samples prepared for each temperature level to ensure repeatability and statistical reliability of the results.

Microstructural investigations were carried out using X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) coupled with Energy Dispersive Spectroscopy (EDS) for both untreated soil and soil subjected to 600 °C thermal treatment. In addition, visual assessment of colour transformation was conducted to document the physical colour changes resulting from heating.

3.Results and discussion

3.1 Particle size distribution (PSD)

The grain-size distribution results show a clear reduction in particle size with increasing temperature, indicating substantial changes in soil structure. The natural soil exhibits a well-graded profile with 100% passing at 0.075 mm, while the 300 °C treated sample shows moderate reduction in fines, reflected by lower percent finer values across all sieve ranges. At 600 °C, the soil undergoes drastic change, with fines almost completely eliminated below 0.3 mm, suggesting particle cementation followed by fragmentation into coarser fractions. This progressive shift from fine rich to a coarse dominated matrix indicates thermal alteration of clay minerals and loss of physicochemical bonds. Overall, heating increases particle aggregation and reduces soil plasticity, leading to a coarser and more open texture that would significantly affect compaction behaviour and strength characteristics (fig.1).

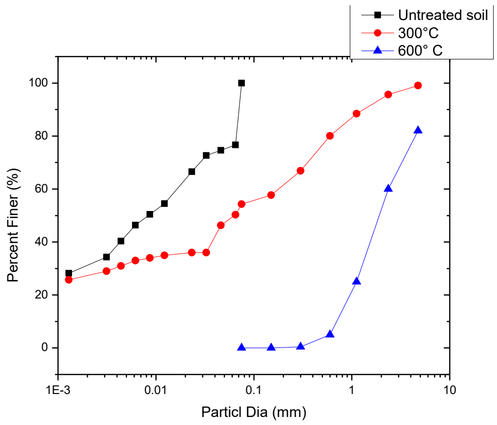

Figure 1: variation of Particle size distribution curve for thermal treatment

3.2 plasticity characteristics

The Atterberg limit results show a pronounced decline in the soil's plasticity with increasing temperature, indicating thermal modification of clay minerals. The liquid and plastic limits remain relatively stable between 27 °C and 110 °C, implying only moisture evaporation without significant structural change. A sharp reduction is observed at 200 °C, where the liquid limit drops from 72.9% to 39.3%, accompanied by a decrease in plastic limit to 20.2%, reflecting the breakdown of physico-chemical bonds and shrinkage of the diffuse double layer. Further heating to 300 °C reduces the liquid limit and plastic limit to 33.1% and 18.2%, respectively, resulting in a plasticity index of 14.9%, which categorises the soil as low-plastic. From 400°C onwards plasticity diminished completely suggests mineral dehydroxylation and reduced water adsorption capacity. Overall, the thermal exposure transforms the soil from highly plastic to marginally plastic, significantly influencing its engineering performance in high-temperature environments (Fig. 2 and Fig. 3).

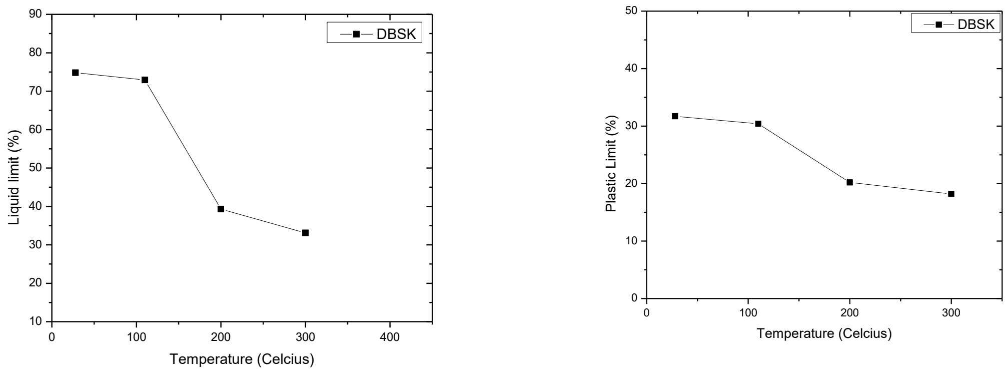

Figure 2: variation of liquid limit and Plastic limit with thermal treatment

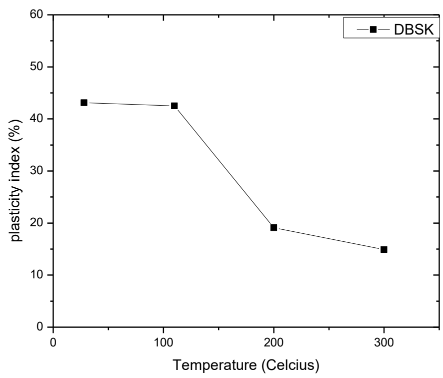

Figure 3: variation of plasticity index with thermal treatment

3.3 compaction characteristics

The compaction characteristics of the soil exhibit a noticeable transformation under thermal exposure, with both OMC and MDD showing temperature dependent variations. The OMC remains constant at 13% up to 110 °C, indicating negligible structural alteration at low temperatures. A gradual decline begins at 200°C, where OMC reduces to 12.5%, corresponding to loss of bound moisture and minor particle rearrangement. At 300 °C, the OMC drops further to 10.1%, while the MDD decreases to 1.40 g/cc, reflecting the onset of thermal weakening and partial collapse of clay aggregates. Beyond 300 °C, the sharp decline in MDD from 1.17 g/cc at 400 °C to 1.15 g/cc at 600 °C suggests significant mineral degradation and increased porosity (Fig. 4). The continuous reduction in OMC at elevated temperatures confirms progressive dehydration and alteration of the soil fabric. Overall, moderate heating improves moisture efficiency, but higher temperatures adversely affect the soil's density and compaction potential due to thermal mineral disruption.

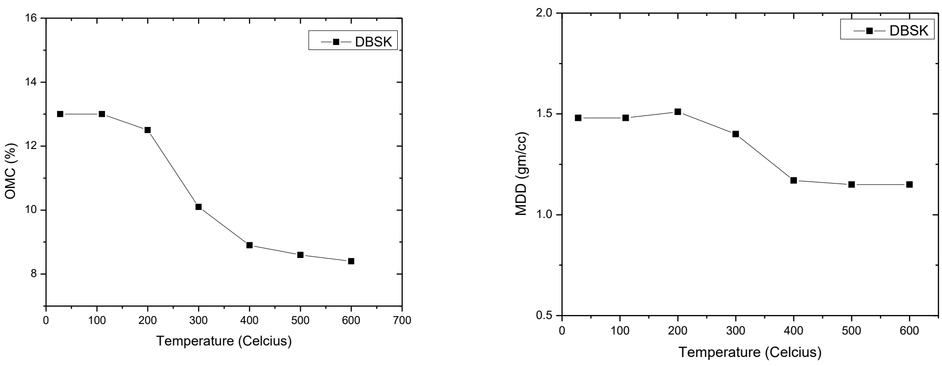

Figure 4: variation of OMC and MDD with thermal treatment

3.4 Direct shear test

The thermal exposure produced a clear, non-linear alteration in the shear strength parameters of the soil. Cohesion (c) exhibited a moderate increase from 60.08 kN/m² at 27 °C to a peak of 62.1 kN/m² at 110 °C, which can be attributed to moisture evaporation and temporary particle interlocking. However, beyond 200 °C, cohesion declined sharply, reducing to 39 kN/m² at 300 °C and further decreased to 15.2 kN/ m². at 500 and 600 °C cohesion collapsed to zero. This drastic loss indicates thermal degradation of clay minerals and structural disintegration.

In contrast, the friction angle (ϕ) showed an opposite trend. It increased from 17.25° at ambient temperature to 23.5° at 200°C, reflecting improved granular contact due to dehydration and shrinkage. At higher temperatures (400–600 °C) the friction angle rose further to 40° to 47°, which suggests transformation towards a more granular, cohesionless state where shear resistance is governed predominantly by particle friction. Overall, the results indicate a transition from a cohesive to a friction dominated material with increasing temperature, which is critical for evaluating soil performance under fire exposure, geothermal effects and high-temperature engineering applications (Fig. 5).

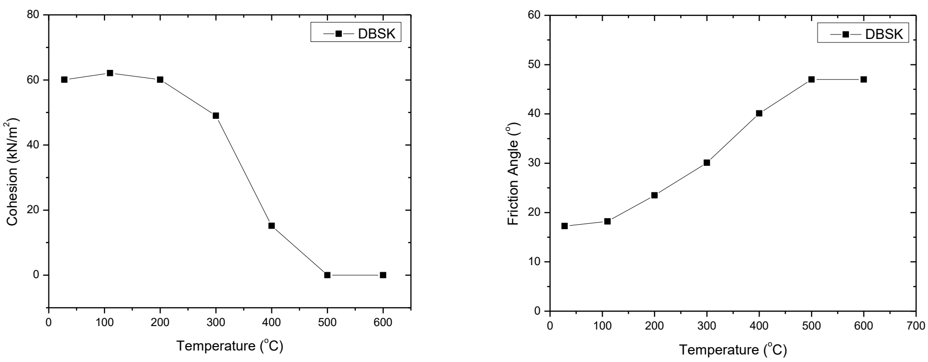

Figure 5: variation of cohesion and friction angle with thermal treatment

3.5 shear strength

The shear strength of DBSK soil shows a distinct temperature dependent behaviour, reflecting the mineralogical and structural changes observed in earlier tests. At low temperatures (27–110 °C), the shear strength increases slightly from 67.7 to 70.2 kPa due to minor moisture loss and improved particle interlocking. A peak value of 71.0 kPa at 200 °C indicates optimal thermal modification, where partial dehydroxylation enhances frictional resistance while cohesion is still retained. Beyond 300 °C, shear strength decreases sharply to 48.9 kPa as clay minerals begin to lose their bonding capacity. At 400 °C and above, the soil transitions into a more granular, non-cohesive material, leading to further reductions to 31.0 kPa and finally stabilizing around 19.7 kPa at 500–600 °C. This trend confirms that high temperature exposure significantly diminishes cohesive strength, aligning with the declining plasticity indices, clay breakdown observed in the study (Fig. 6).

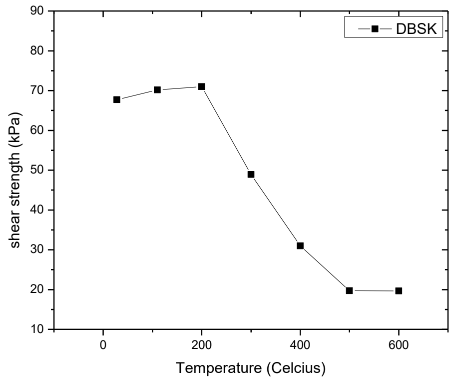

Figure 6: variation of shear strength with thermal treatment

3.6 CBR

The soaked CBR values show a substantial improvement in strength as the soil is subjected to increasing temperatures, indicating significant thermal modification of its structural behaviour. At ambient condition, the CBR is only 1.8%, reflecting weak bearing capacity. A gradual rise up to 3.4% at 200 °C corresponds to partial removal of bound water and initial particle rearrangement. A notable increase occurs at 300 °C, where the CBR reaches 7.9%, suggesting the onset of thermal cementation among clay minerals. Beyond this point, the strength enhancement becomes more pronounced, with CBR values rising sharply to 19.5% at 400 °C and exceeding 24% at 500–600 °C. This substantial improvement indicates the formation of stronger interparticle bonds due to mineral dehydration and possible sintering effects. Overall, the results demonstrate that high temperature treatment significantly enhances the bearing capacity of the soil, transforming it from a low strength material to one with considerable load carrying potential (Fig. 7).

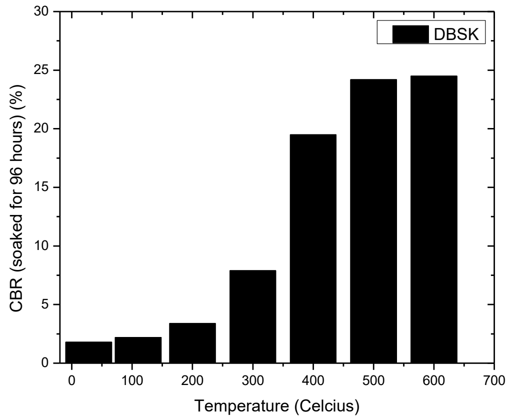

Figure 7: increase of CBR % with thermal treatment

3.7color change phenomenon

The visual inspection of DBSK soil shows a progressive colour change from dark grey in its natural state to reddish brown at 300 °C and a more intense orange red shade at 600 °C. This transformation is primarily attributed to the thermal oxidation of iron-bearing minerals present in the soil. At higher temperatures, Fe^{2+} in minerals iron rich clays oxidises to Fe^{3+}, forming hematite like phases that impart a reddish hue. The change also reflects dehydration and structural breakdown of clay minerals, exposing more iron oxides on particle surfaces. Additionally, organic matter combustion at temperatures above 300 °C contributes to the loss of dark colouring, further enhancing the reddish appearance. Overall, the colour transition signifies mineralogical alteration and oxidation processes, supporting the thermal modification behavior observed in SEM, XRD and strength results (Fig. 8).

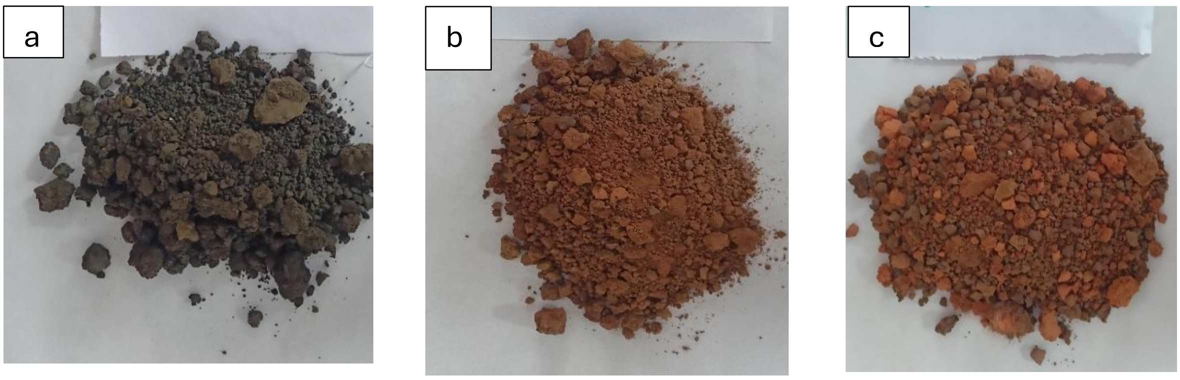

Figure 8: color change phenomenon with thermal treatment a)untreated soil b) 300°C c)600°C thermally treated soils

3.8 SEM

The SEM images clearly illustrate the microstructural transformation induced by thermal treatment. The untreated soil shows a dense assemblage of fine particles with visible clay agglomerations, indicating a cohesive and water sensitive fabric. In contrast, the soil heated to 600 °C exhibits a more fragmented and granular structure, with larger, rigid particles and reduced surface smoothness. This breakup of clay clusters suggests dehydroxylation and collapse of the diffuse double layer, leading to diminished plasticity. The formation of sharper-edged and cemented particles is consistent with the rise in CaO content, which promotes mineral bonding at elevated temperatures. Such microstructural densification and partial sintering explain the significant increase in CBR values after heating, confirming that high-temperature exposure enhances soil strength by improving interparticle contact and reducing its cohesive, clay like behaviour (Fig. 9 and Fig. 10).

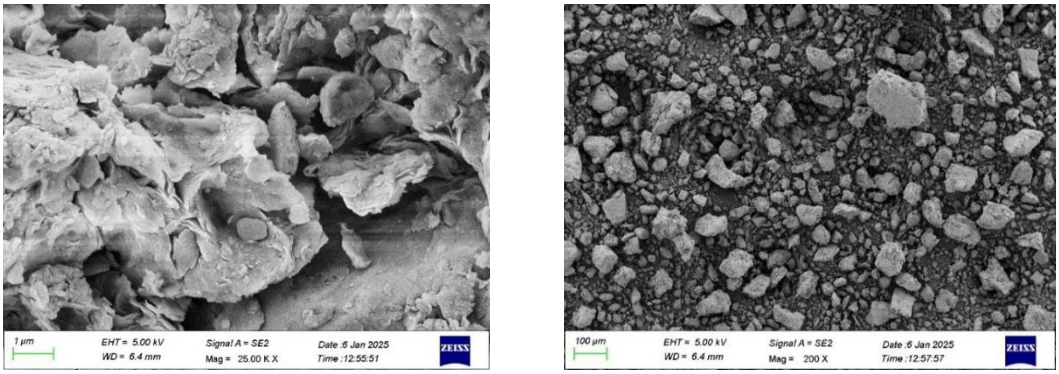

Figure 9: morphology of untreated DBSK soil

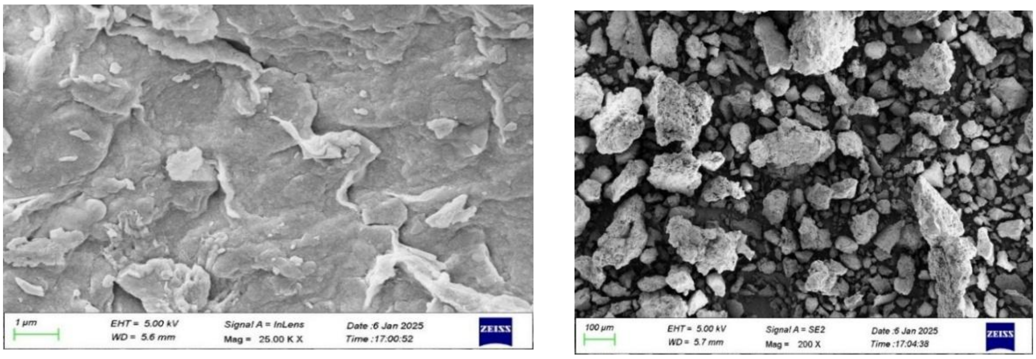

Figure 10: morphology of 600°C heated soil

3.9 XRD

The XRD comparison of untreated and thermally treated soil reveals distinct mineralogical changes driven by heating. The untreated sample displays characteristic peaks of quartz, feldspar and clay minerals such as kaolinite and illite, identifiable through the broad, low-intensity reflections typically associated with layered silicates.

After heating to 600 °C, the diffraction pattern shows sharper and more intense peaks, particularly near 26° (2θ), confirming the dominance of crystalline quartz. Several low angle peaks associated with kaolinite and illite disappeared, indicating dehydroxylation and partial structural collapse of clay minerals. The emergence of more defined feldspar peaks suggests thermal recrystallization of aluminosilicate phases. Overall, the XRD results demonstrate a transition from a clay rich, partially amorphous structure to a more crystalline quartz feldspar matrix, explaining the enhanced stiffness and strength observed in the thermally treated soil.

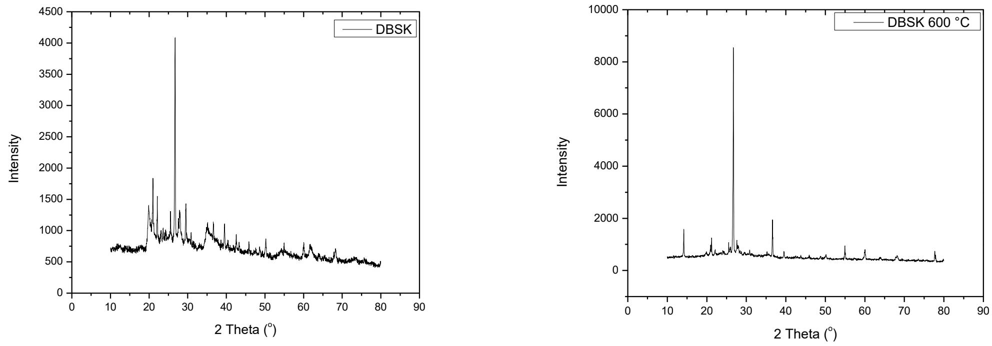

Figure 11: variation of XRD plots with thermal treatement a)untreated soil b) 600°C

3.10 chemical composition

The oxide composition analysis shows that thermal treatment up to 600 °C causes distinct chemical changes in the soil, with CaO showing the most significant increase from 4.70% to 6.96%. This rise in CaO indicates decomposition of calcium bearing minerals and the release of reactive lime phases during heating. These liberated calcium compounds promote cementitious reactions and strengthen interparticle bonding, which directly correlates with the substantial increase in soaked CBR values observed at higher temperatures. While minor variations occur in SiO_2, Al_2O_3 and Fe_2O_3, it is the pronounced CaO enrichment that plays the dominant role in enhancing the soil's load bearing capacity. Overall, the results confirm that thermal activation elevates the calcium reactivity within the soil, leading to improved stability and mechanical performance.

Table 2: variation of chemical composition with thermal treatment of the soil

Oxide	Weight % (natural soil)	Weight % (600 °C heated soil)
SiO_2	54.95%	55.41%
Al_2O_3	18.99%	18.01%
CaO	4.70%	6.96%
Fe_2O_3	10.30%	11.47%
MgO	4.95%	3.00%
Na_2O	3.75%	3.15%
K_2O	2.36%	2.00%

4. Conclusion

Temperature significantly influences soil shear strength, causing non linear changes in cohesion and friction angle across the tested range of 27–600 °C. Cohesion reduced to zero at 500°C, confirming that the soil transforms into a predominantly frictional material after severe thermal exposure. Friction angle showed a continuous increase with temperature, rising from 17° at ambient conditions to about 47° at 600 °C, due to improved grain-to-grain contact and reduction of adsorbed water layers. Overall shear strength transitioned from cohesion controlled to friction controlled as temperature increased, demonstrating fundamental changes in soil behaviour under thermal loading. These results highlight the need for temperature dependent design considerations in geotechnical applications involving fire exposure, geothermal structures, high-temperature waste facilities and underground energy systems. The study provides valuable data for developing thermal mechanical models and improving prediction of soil strength deterioration at elevated temperatures.

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