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Geotechnical and Mineralogical Transformations of Low Plastic clay Soils under Elevated Temperatures

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***Abstract* - This study investigates the influence of thermal treatment on the geotechnical and mineralogical behavior of two low-plasticity clayey soils (RSB and KNWS) subjected to controlled heating between 110°C and 600°C. A comprehensive experimental program involving Atterberg limits, compaction, direct shear, CBR, oxide composition, SEM and XRD analysis was conducted to correlate engineering performance with microstructural and mineralogical transformations. The results show that heating progressively reduced plasticity in both soils, with KNWS exhibiting a sharper reduction due to its higher clay sensitivity. Compaction characteristics improved notably with temperature, as the optimum moisture content decreased and the maximum dry density increased 9%, indicating densification and breakdown of bound water. Direct shear test results reflected a transition toward granular behavior, with cohesion decreasing at higher temperatures and friction angle increased 14%. Soaked CBR values exhibited significant enhancement, rising from 0.9% to 17.4% in RSB and from 10.1% to 17.9% in KNWS at 600°C, primarily due to particle rearrangement and reduction in clay activity. Oxide analysis revealed increased concentrations of CaO indicating dehydroxylation and partial decarbonation of minerals. SEM images confirmed particle fusion, aggregation and pore reduction at elevated temperatures, while XRD results showed the disappearance of kaolinite and illite peaks and the persistence of quartz and feldspar phases. Overall, the study demonstrates that thermal treatment significantly enhances the engineering properties of low-plastic soils by inducing structural reorganization and mineral transformations, highlighting its potential as a sustainable and eco-friendly soil improvement technique.**

Keywords: Thermal treatment, Clayey soils, Compaction, Strength, Mineralogy, Heating temperature

1. INTRODUCTION

Stabilization of soil is very common now a days to make use of soil, to improve soil properties according to our need. Chemical stabilization is very common now a days. But as part of using chemicals strength and working properties are improved but people are forgetting or not looking at sustainable point of view. As sustainable point chemical stabilization consequences are leading to dangerous situations like ground water, surface water contamination, thermal stabilization is a promising technique in sustainable point of view. Most of thermal stabilization studies on high plastic clays, soils with high clay content, this paper concentrates on the low plastic clays with less clay content how the soil will behave with increase of temperature effect. This paper gives insights to effect of thermal stabilization on low plastic clays. This paper is an attempt to study thermal effect on clays with low plasticity. Thermal exposure has emerged as a promising and sustainable alternative to chemical stabilization for modifying the engineering behavior of soils. Conventional chemical agents such as lime, cement, fly ash and industrial by-products are effective in improving strength and workability; however, they raise environmental concerns including groundwater contamination, carbon emissions and long-term durability issues due to leaching of ions. In contrast, thermal treatment alters soil behavior through physical and mineralogical processes such as dehydration, dehydroxylation, particle aggregation and restructuring of clay minerals, making it a cleaner and more environmentally responsible technique.

Several researchers have examined the thermal sensitivity of fine-grained soils. Abu-Zreig et al. (2001) showed that heating clayey soils between 100–400 °C significantly reduces plasticity due to the removal of absorbed and structural water from clay minerals. Attah and Etim (2020) reported that tropical residual soils subjected to temperatures up to 400 °C exhibited lower optimum moisture content, higher maximum dry density, and improved bearing capacity, primarily due to breakdown of diffuse double layers and densification of the soil fabric. Attah et al. (2020) further demonstrated that heating causes clay minerals such as kaolinite and smectite to undergo dehydroxylation, forming amorphous metaclay phases that enhance frictional resistance and reduce shrink–swell behavior. Similarly, Hueckel and Baldi (1990) and Demars and Charles (1982) identified that thermal loads cause irreversible structural changes in clays due to collapse of interlayer spacing and expulsion of bonded water.

Despite these advancements, most earlier studies focus on highly plastic soils with significant clay activity. The literature lacks sufficient data on low-plasticity and low-clay-content soils, which may respond differently due to their larger proportion of silt/sand-sized particles and weaker clay–water bonds. The limited studies available indicate that low-plastic soils may exhibit more granular behavior after heating, but comprehensive results correlating geotechnical and mineralogical changes remain scarce. Furthermore, the role of mineral transformations such as decomposition of carbonates, formation of oxides, collapse of layered clays, and concentration of silica-rich phases in controlling engineering behavior is not yet fully understood for these soil types.

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In this context, the present research investigates two low-plasticity soils RSB and KNWS subjected to controlled heating from 110 °C to 600 °C for 180 minutes. The study integrates geotechnical tests with mineralogical analyses (oxidation profiling, SEM morphology and XRD phase identification) to comprehensively understand how thermal exposure influences engineering and structural properties.

Overall, this work contributes to filling the literature gap by providing detailed insights into the thermal behavior of low-plastic soils. The findings highlight the potential of thermal modification as a reliable, eco-friendly stabilization technique suitable for fire-affected soils, thermal foundations, and sustainable infrastructure applications.

2. MATERIALS AND METHODS

2.1 *Soil Sampling and Site Description*

Two natural soils were selected for this investigation. RSB Soil (Red Soil Bhairav Nagar) collected from Bhairav Nagar region, Anantapur District, Andhra Pradesh characterized by reddish coloration. The coordinates of the location are 14.639243916159682^0, 77.60697647361307^0. KNWS Soil (Kovur Nagar White Soil) Collected from Kovur Nagar, Anantapur District, Andhra Pradesh, dominated by lighter-colored. The coordinates of the soil collected location are 14.672384338727484^0, 77.58427756326137^0.

Both soils were collected at a depth of 1.5 m below ground level to avoid organic matter, topsoil contamination and external environmental influences. Disturbed soil samples were collected in airtight polythene bags, sealed immediately to preserve natural moisture and transported to the geotechnical laboratory.

2.2 *Basic Soil Characterization*

The collected samples were oven-dried, pulverized prior to characterization. The following preliminary tests were conducted Particle size distribution (IS: 2720 Part 4), Atterberg limits (IS: 2720 Part 5), Specific gravity (IS: 2720 Part 3), Standard Proctor compaction test (IS: 2720 Part 7), Natural moisture content (IS: 2720 Part 2). These baseline tests established the physical and index properties of RSB and KNWS soils (Table 1).

Table 1: basic and index properties of the soils

Property	RSB	KNWS
Natural Moisture content	19.8	10.7
Liquid limit (%)	22.0	35.1
Plastic limit(%)	15.2	22.3
Plasticity index	6.8	15.1
Specific gravity	2.68	2.68
USCS symbol	CL-ML	CL
Maximum dry density (kN/m^3)	2.1	1.8
Optimum moisture content (w_{opt}) (%)	12	10.8
Gravel (> 4.75 mm)(%)	0	5.1
Sand (4.75 mm – 75 µm) (%)	74.3	75.8
Silt (75 µm – 2 µm) (%)	22.5	12.9
Clay (< 2 µm) (%)	3.2	6.2

2.3 *Thermal Treatment Procedure*

Soil samples were subjected to controlled heating at 110°C, 200°C, 300°C, 400°C, 500°C and 600°C. Air-dried soil was spread uniformly in ceramic trays. Heating was performed in a muffle furnace. Each sample was heated for 180 minutes (3 hours) at the target temperature. Temperature was raised gradually (5°C/min) to avoid thermal shock. After heating, samples were cooled inside the furnace to room temperature to prevent micro-cracking. Cooled samples were stored in sealed containers. The heated soil was pulverised using a wooden mallet and sent for sample preparation of various testing.

2.4 *Experimental Program*

A comprehensive testing program was developed to study geotechnical, chemical and mineralogical changes due to heating. sieve analysis and hydrometer analysis (IS: 2720 Part 4). Liquid limit (LL) and plastic limit (PL) were determined for both untreated and heated soils using Casagrande device and rolling thread method. Standard Proctor compaction tests were conducted at each temperature level to determine Optimum Moisture Content (OMC), Maximum Dry Density (MDD), Direct shear tests were performed using a strain-controlled shear box apparatus at a normal stress of 50, 100 and 150 kPa (IS: 2720 Part 13), Soaked CBR tests (IS: 2720 Part 16) were carried out on compacted specimens for each temperature condition.Samples were soaked for 96 hours prior to testing. CBR results were used to determine the improvement in subgrade performance due to heating.

Chemical and Mineralogical Analysis conducted. Major oxides including SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, Na_2O and K_2O were analyzed for untreated and 600°C heated soils using EDS attached to SEM. The changes indicated mineral decomposition, decarbonation and concentration of stable phases. SEM imaging was conducted for untreated soil microstructure, 600°C heated soil morphology. XRD analysis was performed to identify mineral phases before and after heating at 600°C.

3. RESULTS AND DISCUSSION

3.1 *Particle size distribution*

Thermal treatment produced distinct yet comparable modifications in the particle size distribution (PSD) of both RSB and KNWS soils, reflecting temperature-dependent structural rearrangements. In their natural state, both soils exhibited a well graded mixture with relatively higher fines content in RSB compared with KNWS. Mild heating up to 110 to 200 °C caused only marginal fluctuations in both soils, attributable mainly to evaporation of hygroscopic and adsorbed water without inducing major mineral disruption. However, between 300 to 400 °C, clear shifts emerged, RSB showed a reduction in fine fractions (0.30–0.15 mm) and KNWS exhibited decreased percent finer values in the 2.36–1.18 mm range, suggesting breakdown of clay particle bondings, collapse of interlayer spacing and the onset of dehydroxylation. The behavior intensified at higher temperatures 500 to 600 °C both soils displayed a pronounced reduction in fines, with the 0.075 mm fraction dropping to zero in RSB and to only 3% in KNWS, while coarse and intermediate fractions became more dominant. This indicates advanced mineral decomposition, burning of organics, and thermal fusion of particles leading to aggregation and coarsening. RSB showed stronger particle aggregation at high temperatures, evidenced by a sharper reduction in fines relative to KNWS, likely due to higher clay reactivity. KNWS, although similarly affected, exhibited a more gradual coarsening trend. Overall, both soils transitioned from a fine gradation to a coarser structure as temperature increased, driven by dehydration, dehydroxylation processes of clay minerals.

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These PSD changes for untreated, 300°C and 600°C are showed in fig.1 and fig. 2.

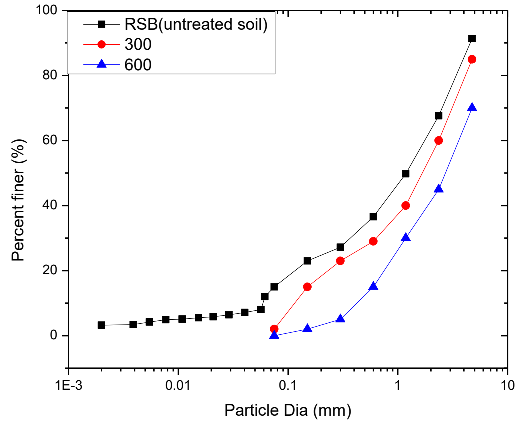

Figure 1: variation of PSD curve with thermal treatement of RSB soil

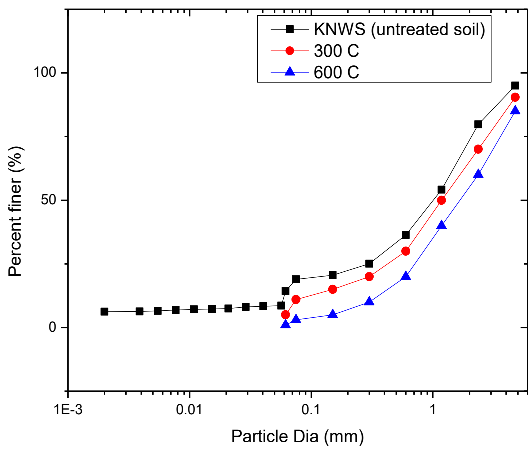

Figure 2: variation of PSD curve with thermal treatement of KNWS soil

3.2 *3.2 Plasticity Characteristics*

The plasticity behavior of both RSB and KNWS soils shows consistent but soil-specific changes with respect to thermal exposure, reflecting differences in mineralogy and clay activity. For RSB soil, the liquid limit remained unchanged at 22% between 27 °C and 110 °C, while the plastic limit decreased slightly from 15.2% to 14.7%, resulting in a marginal increase in plasticity index (6.8% to 7.0%). This negligible variation indicates that low-temperature heating removes only free and adsorbed moisture without significantly affecting the interlayer structure or diffuse double-layer thickness of RSB soil, which is characteristic of low-reactivity clays. In contrast, KNWS soil exhibited more pronounced changes, particularly at temperatures above 110 °C. While KNWS behaved similarly to RSB up to 110 °C with liquid limit unchanged at 35.1% and only a slight adjustment in plastic limit. The liquid limit dropped sharply to 24.7% at 200 °C and the plastic limit reduced to 15.1%, resulting in a substantial decline in plasticity index from 12.8% to 9.6%(Figure 3 and Figure 4). This strong reduction indicates the onset of structural water loss and partial dehydroxylation, which lowers the soil's ability to maintain adsorbed water films and reduces its swelling, shrinkage potential. The sharper decline in KNWS compared to RSB suggests that KNWS contains more thermally sensitive clay minerals that undergo early structural breakdown when heated. Overall, RSB shows thermal stability up to 110 °C, KNWS begins to lose plasticity significantly at 200 °C, marking a transition toward reduced interparticle forces. These results align with established thermal behavior of fine-grained soils, where plasticity decreases rapidly once structural water is released above 200 °C (Figure 5).

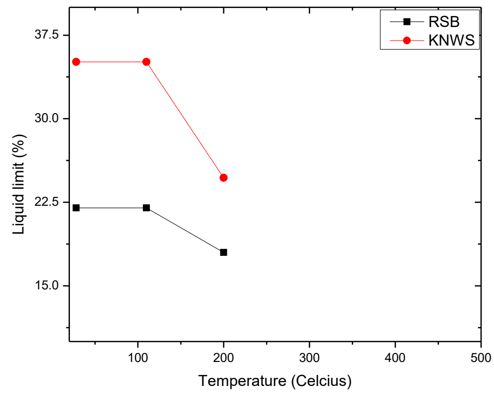

Figure 3: variation of liquid limit with thermal treatment

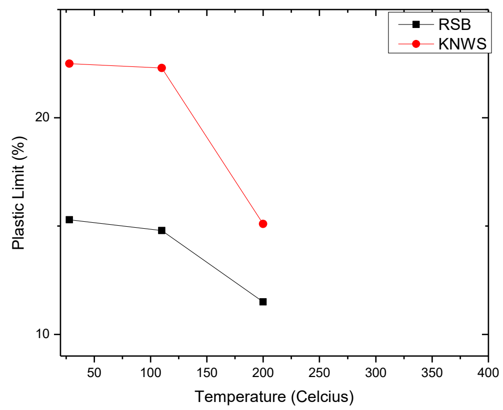

Figure 4: variation of plastic limit with thermal treatment

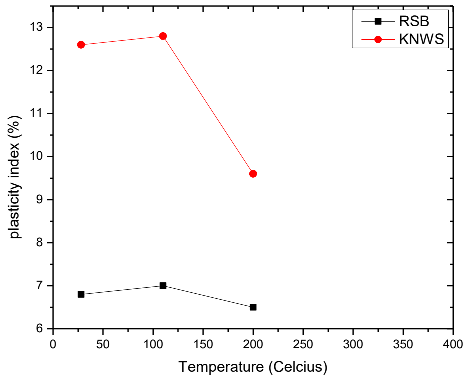

Figure 5: variation of plasticity index with thermal treatment

3.3 *Compaction Charcteristics*

Both RSB and KNWS soils exhibited a similar compaction behaviour with respect to thermal exposure, showing a progressive decrease in OMC and a corresponding increase in MDD with increasing temperature. At room temperature (27 °C), both soils RSB,KNWS recorded an OMC of 12%, 11% and

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an MDD of 2.1 g/cc, 1.9 g/cc respectively. Heating the soils up to 110 °C did not produce any significant change, indicating that removal of free water alone has a limited influence on compaction parameters. Noticeable variations started beyond 200 °C, where the OMC of both RSB and KNWS soils reduced to around 11.5% due to the loss of adsorbed water and partial disturbance of the diffuse double layer. As the temperature increased to 300 °C and further to 400–600 °C, OMC gradually decreased to 9.8%, 9.4% while MDD increased consistently to 2.3 g/cc, 2.1 g/cc for RSB and KNWS respectively (Figure 6).

The increasing MDD trend in both deposits can be attributed to thermal dehydration, loss of bound water, breakdown of inter-particle bonding and partial collapse of the clay fabric, resulting in the formation of denser and more compactable soil structures. The stabilization of MDD at 2.3 g/cc beyond 400 °C indicates that major dehydration and structural rearrangements were completed by this temperature range. The nearly identical thermal response of the two soils suggests that both RSB and KNWS soils possess comparable clay mineral assemblages. Overall, the results confirm that controlled heating significantly enhances the dry density and reduces the moisture demand of both soils (Figure 7).

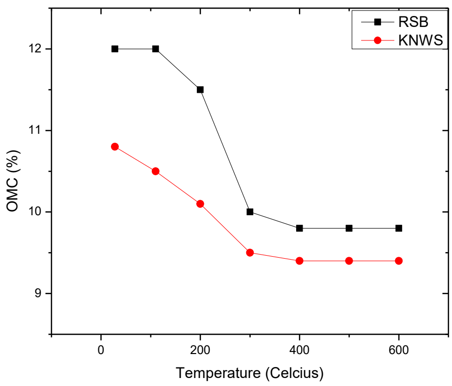

Figure 6: variation of OMC with thermal treatment of the soils

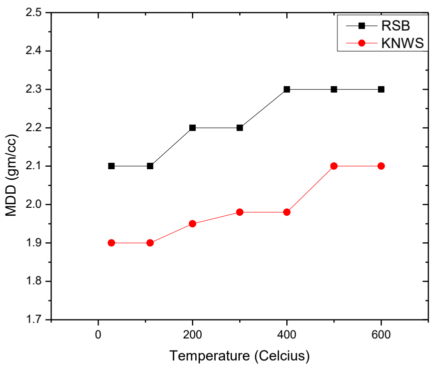

Figure 7: variation of MDD with thermal treatment of the soils

3.4 *Direct shear test*

3.4.1 Cohesion

Both RSB and KNWS soils exhibited a consistent thermal response in terms of shear strength characteristics. The magnitude of variation differed significantly due to differences in their initial clay content, mineralogy and bonding mechanisms. In both soils, the cohesion remained nearly unchanged up to 110 °C, reflecting that removal of free pore water does not alter the inter-particle bonding. Beyond 200 °C, a clear reduction in cohesion was observed. For RSB soil, cohesion decreased moderately from 10.5 kN/m² to around 5.3 kN/m² at 200 °C, indicating partial breakdown of adsorbed-water films and weak cementitious bonds. In contrast, KNWS soil showed a much sharper decline from 41.18 kN/m² at room temperature to nearly 10.2 kN/m² at 400 °C. The soil initially possessed stronger clay–water and inter-particle bonds which were significantly weakened by thermal exposure. This large drop signifies extensive dehydration, collapse of the diffuse double layer (Figure 8).

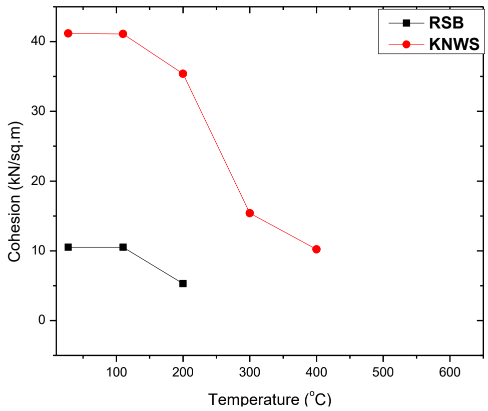

Figure 8: variation of cohesion of the soil with thermal treatment

3.4.2 Friction angle

While cohesion decreased in both soils, the friction angle showed an opposite trend. RSB soil exhibited an increase from 40° to 44°, and KNWS soil increased from 42° to 45° with increasing temperature. This rise in friction angle is attributed to transformation of the clayey matrix into a denser, granular structure as water is expelled, pore spaces reduce, and particle contacts shift from diffuse double-layer dominated to skeleton friction-dominated behaviour. The more pronounced increase in friction angle for both soils indicates greater particle rearrangement and aggregation due to stronger dehydration-induced structural changes.

Overall, thermal treatment drives both soils toward a frictional, granular behaviour. KNWS soil shows a much sharper reduction in cohesion due to its initially higher clay content and stronger bonding, whereas RSB soil exhibits milder changes due to its comparatively weaker clay fabric. Despite this, the increase in friction angle in both soils suggests improved shear resistance at higher confining pressures after heating, which is beneficial for applications involving thermally modified or fire-affected soils (Figure 9).

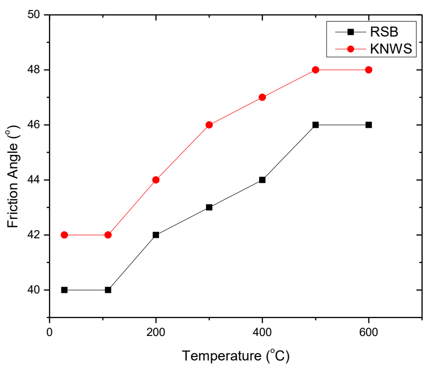

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Figure 9: variation of friction angle of the soils with thermal treatment

3.5 *CBR*

Both RSB and KNWS soils exhibited a substantial improvement in soaked CBR values with increasing temperature; however, the magnitude of improvement differed significantly due to variations in initial soil composition and clay content. In their natural state (27 °C), KNWS soil showed a much higher CBR (6.5%) compared to RSB soil (0.9%), indicating superior inherent strength and lower plasticity of KNWS. Heating up to 110 °C produced only marginal improvements in both soils, reflecting the limited influence of removing free water. A notable enhancement in CBR was observed beyond 200 °C in both soils.

For RSB, CBR increased sharply from 4.5% at 200 °C to 12.5% at 400 °C, whereas KNWS improved from 12.4% to 15.6% over the same temperature range. This improvement is associated with the loss of adsorbed water, reduction in plasticity, and densification of the soil structure.

At higher temperatures (400–600 °C), both soils achieved their maximum CBR percentage. RSB reached 17.4% at 600 °C, while KNWS achieved a slightly higher value of 17.9%. Although the final CBR values are comparable, the response mechanism differs: RSB soil undergoes a transformation from a weak clayey material to a densely packed, granular-like matrix due to extensive dehydration and partial clay mineral alteration. In contrast, KNWS soil, which already possesses higher initial strength, experiences moderate structural modification and particle rearrangement that enhance its CBR values further.

The overall trend shows that thermal treatment significantly enhances the penetration resistance, densification and load-bearing capacity of both soils. The improvement corresponds well with the observed increase in MDD and reduction in OMC, indicating that heating promotes stronger particle interlock and improved compaction efficiency. This suggests that controlled thermal modification can effectively improve subgrade performance of both clayey soils (Figure 10).

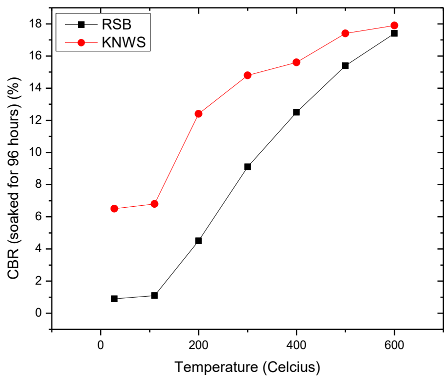


Figure 10: variation of CBR % with thermal treatment

3.6 *Chemical Composition*

This analysis is carried out with Energy Dispersive X-ray Spectroscopy in Scanning Electron Microscopy. The chemical changes indicate that heating induces dehydroxylation of silicate minerals, concentration of improved Ca phases and reduction of volatile or oxidation sensitive oxides. These transformations directly correlate with the improvement in engineering properties such as reduced plasticity, increased MDD, higher friction angle, and enhanced CBR, as the soil structure transitions into a denser, more granular and mechanically stronger matrix at elevated temperatures (Figure 11).

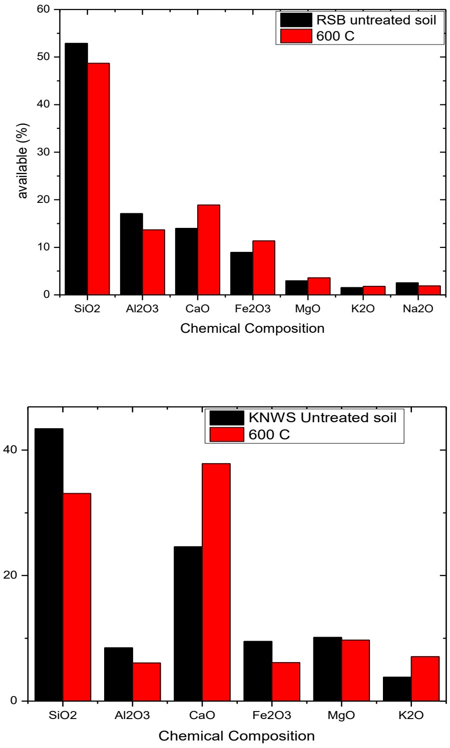
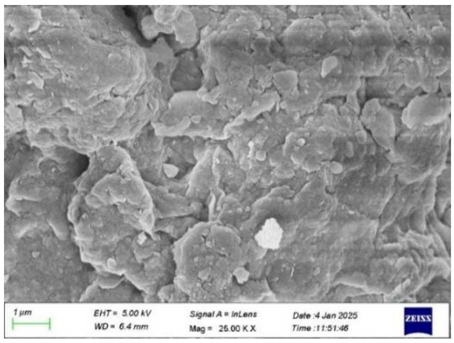


Figure 11: variation of two soils chemical composition(%) with thermal treatment

3.7 *SEM analysis*

SEM images of both RSB and KNWS soils show that the untreated samples possess a loose and porous microstructure with scattered clay. This indicates the presence of adsorbed water layers and weak inter-particle bonding (Figure 12 and Figure 14). After thermal treatment, both soils show a progressive change in fabric. At higher temperatures (600 °C), the microstructure becomes denser, with fused clusters, increased voids, and partially vitrified surfaces. RSB soil generally shows slightly smoother fused masses at 600 °C, while KNWS soil displays more granular and blocky structures due to its higher CaO content. Overall, SEM images of both soils confirm that heating leads to improved pore spaces, stronger particle bonding, and a transition from a flocculated to a compact, sintered structure, supporting the improvements in compaction and strength properties(Figure 13 and Figure 15).



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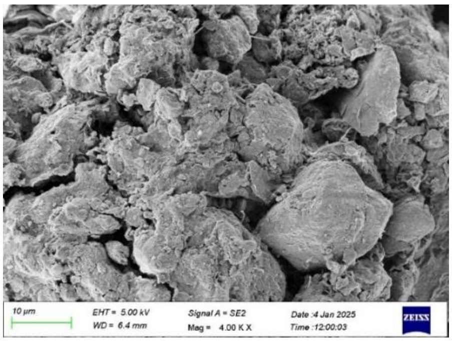

Figure 12: morphology of RSB untreated soil

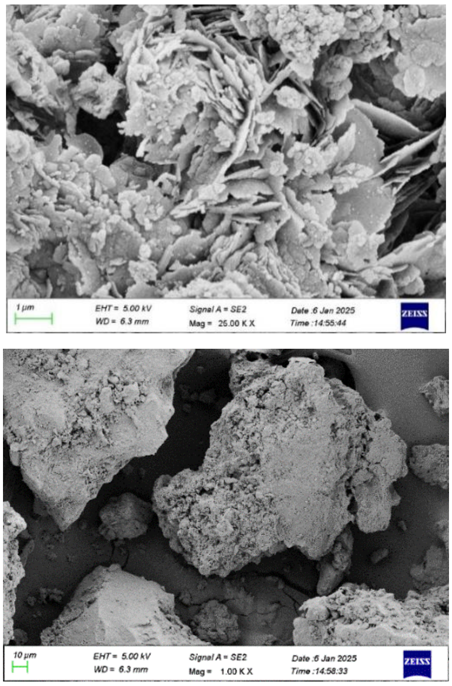

Figure 13: morphology of RSB 600°C heated soil

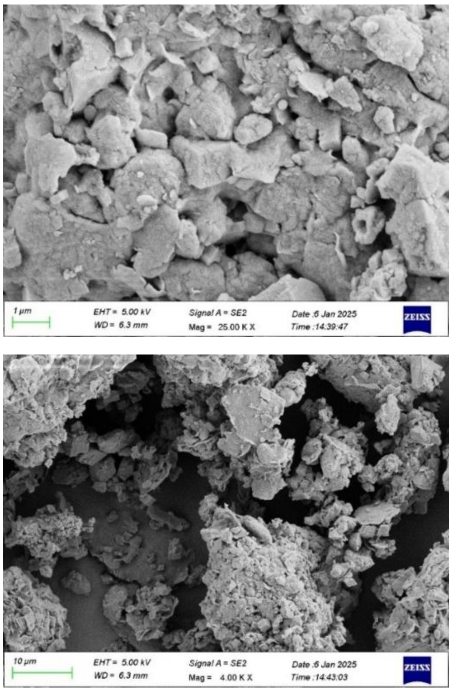

Figure 14: morphology of KNWS untreated soil

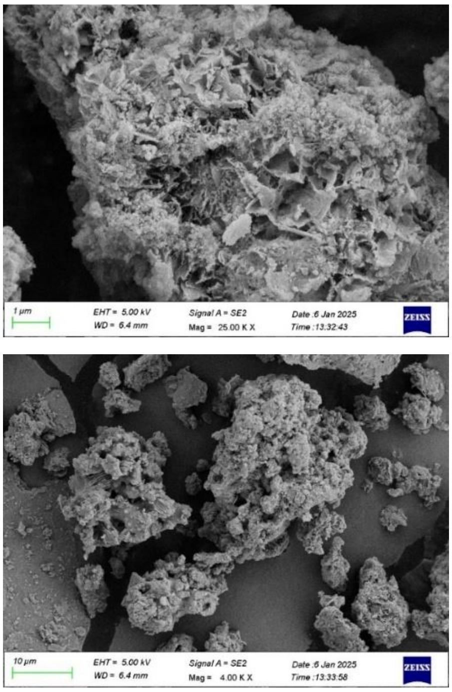

Figure 15: morphology of KNWS 600°C heated soil

3.8 *XRD analysis*

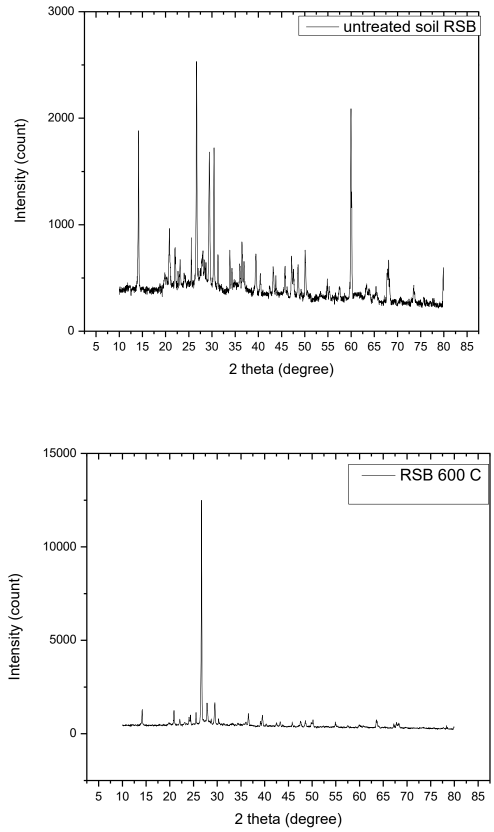

Figure 16: XRD analysis for RSB soil

The X-ray diffraction (XRD) patterns of the RSB soil, before and after thermal treatment at 600 °C, reveal notable mineralogical transformations. In the untreated soil, the dominant phases were quartz, calcite, K-feldspar (microcline/orthoclase), and plagioclase (albite/oligoclase),

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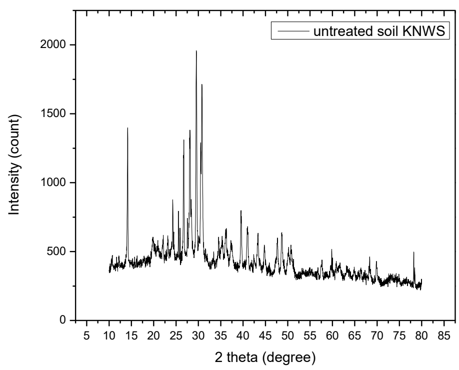
accompanied by minor quantities of dolomite, anatase and trace levels of clay minerals such as montmorillonite, illite and kaolinite. After heating to 600 °C, the mineral composition shifted distinctly. The clay mineral peaks (illite, kaolinite) diminished or disappeared due to dehydroxylation and collapse of the layered structures, marking the transformation into amorphous metaclay. The spectrum is dominated by quartz, feldspars and calcite, with additional reflections attributable to hematite (Fe_2O_3) and traces of anatase (TiO_2). The persistence of quartz and feldspars confirms their thermal stability, while the emergence of hematite peaks near 33°–36° 2θ suggests oxidation of iron-bearing phases during heating. The reduction in carbonate intensity implies partial decarbonation of calcite and dolomite, typical of reactions initiating 600°C. Overall, heating resulted in the loss of clay crystallinity, stabilization of silicate minerals, and partial formation of oxides, signifying structural reorganization of the soil matrix toward a more granular and thermally altered phase (Figure 16).



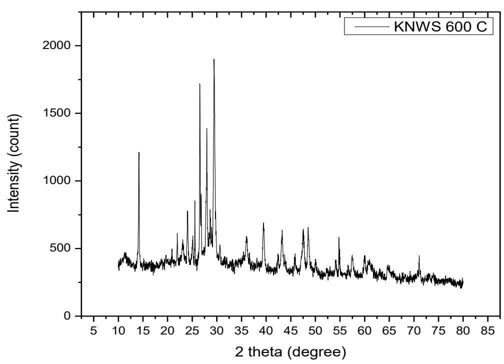


Figure 17: XRD analysis of KNWS soil

The X-ray diffraction (XRD) analysis of KNWS soil after thermal treatment at 600 °C revealed major mineralogical changes compared to its natural condition. The untreated soil exhibited a mixed mineralogical composition dominated by quartz, K-feldspar and plagioclase, with subordinate calcite, dolomite and minor clay minerals such as illite, kaolinite. Upon heating to 600 °C, the XRD pattern showed a significant reduction in the intensity of the clay mineral peaks, indicating the dehydroxylation and structural collapse of the layered silicate phases. The characteristic kaolinite reflections at around 12.36° and 24.88° 2θ disappeared, confirming its transformation to metakaolin. Similarly, the broad peaks associated with illite near 5–8° 2θ were absent, suggesting interlayer water loss and irreversible collapse of the clay structure. Quartz and alumino silicate minerals are stable upto 600°C (Figure 17).

Overall, the heating process induced dehydroxylation of clays, partial decarbonation of carbonates and oxide formation, leading to a more crystalline and thermally stabilized mineral assemblage. These transformations suggest that controlled heating at 600 °C markedly enhances the thermal durability and structural rigidity of KNWS and RSB soils by converting plastic clay into non-plastic, inert mineral phases.

4. CONCLUSIONS

This study evaluated the geotechnical and mineralogical response of two low-plasticity soils (RSB and KNWS) subjected to controlled heating from 110°C to 600°C. Based on the experimental investigations and supporting microstructural analyses, the following conclusions are drawn:

- **Thermal treatment significantly modifies soil behavior**, even in low-plasticity soils with limited clay content. The reduction in adsorbed water, breakdown of clay water bonds and structural rearrangements strongly influence index, strength and compaction properties.

- **Plasticity decreased progressively with temperature** for both soils. KNWS showed a sharper reduction in liquid limit and plasticity index due to its higher content of thermally sensitive clay minerals, indicating early dehydration and dehydroxylation.

- **Compaction characteristics improved substantially**, with OMC decreasing and MDD increasing for RSB (2.1 g/cc to 2.3 g/cc)and for KNWS (1.9 gm/cc to 2.1 gm/cc) for as temperature increased. This behavior was governed by the loss of bound water, fabric densification and the development of a more granular soil structure.

- **Soil behavior exhibited a transition from cohesive to frictional dominance.** Cohesion reduced at higher temperatures due to breakdown of clay and disruption of cementitious bonds, while friction angle increased for RSB(40–46°) for KNWS (42–48°), reflecting increased particle interlock and granular behavior.

- **Soaked CBR values increased remarkably** across the temperature range. RSB improved from 0.9% to 17.4% and KNWS increased from 10.1% to 17.9% at 600°C. The enhancements are associated with densification, reduction in clay activity, and formation of more stable particle matrices.

- **Chemical composition changed significantly** at 600°C. The reduction in SiO_2, Al_2O_3, increase in CaO, and K_2O indicate dehydroxylation of clay minerals, partial decarbonation of carbonates and concentration of stable high-temperature oxides.

- **SEM analysis confirmed microstructural reorganization**, showing particle fusion, collapse of fine clay textures, pore reduction and formation of aggregated granular structures at elevated temperatures.

- **XRD results revealed disappearance of clay mineral peaks** (kaolinite, illite) and persistence of quartz and feldspar, indicating that heating transforms clay minerals into amorphous, metaclay phases and stabilizes silicate minerals.

• **Thermal stabilization is effective even for low-plastic soils**, contrary to the assumption that only high-plastic clays exhibit significant thermal sensitivity. Both soils demonstrated major geotechnical improvements with rising temperature.

Overall, the study establishes thermal treatment as a sustainable soil improvement technique, capable of enhancing strength, reducing plasticity and improving compaction characteristics without chemical additives. This method is particularly relevant for fire-affected soils, thermal foundations, pavement subgrades and environmentally sensitive construction projects.

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