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Effects of elevated temperature and treatment duration on selected index and engineering properties of lateritic soils

Lekan Olatayo Afolagboye[1] · Olubunmi Oluwadare Owoyemi[2] · Yusuf Ademola Abdu-Raheem[1] · Aderemi Sunday Adeoye[1]

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Abstract
Lateritic soils are important to various engineering applications, especially in tropical regions, where they serve as key components in road construction, embankments, and other geotechnical structures. This study investigated the combined effects of elevated temperature and heating duration on the index and engineering properties of lateritic soils derived from two distinct parent rocks (charnockite and quartzite) in Ado-Ekiti, Nigeria. Disturbed lateritic soil samples were heated in a furnace at various temperatures (100, 200, 300, and 400 °C) for two designated durations (2 and 3 h). Standard geotechnical tests were conducted to evaluate Atterberg limits, compaction parameters, and unconfined compressive strength. The results showed that elevated temperature led to a decrease in the plastic limit, liquid limit, plasticity index, optimum moisture content (OMC), and UCS for both soils, though the extent varied between the two parent rocks. For instance, at 400 °C for 3 h, the plasticity index decreased by 47.82% for charnockite-derived soil and 55.22% for quartzite-derived soil. At the same temperature for 2 h, it decreased by 38.79% for charnockite-derived soil and 48.92% for quartzite-derived soil. Similarly, UCS decreased by 29.83% for charnockite-derived soil and 25.97% for quartzite-derived soil at 400 °C for 3 h, while at 400 °C for 2 h, UCS decreased by 21.20% for charnockite-derived soil and 23.48% for quartzite-derived soil. Conversely, maximum dry density (MDD) increased with temperature, rising by up to 20.64% for charnockite-derived soil and 14.66% for quartzite-derived soil at 400 °C for 3 h, and by 18.29% for charnockite-derived soil and 12.62% for quartzite-derived soil at 400 °C for 2 h. Longer heating durations (3 h) generally caused more pronounced changes in soil properties compared to shorter durations (2 h). For instance, OMC decreased by 13.41% for charnockite and 14.18% for quartzite at 400 °C for 3 h compared to a 2-h duration. Statistical analyses indicated that temperature had a significant influence on most properties, while the effect of heating duration was less consistent. These findings highlight the need to consider both temperature and heating duration when evaluating the engineering behavior of lateritic soils exposed to elevated temperatures. Practical implications include potential adjustments in construction practices and design parameters for road construction and embankments in regions prone to high temperatures, such as those experiencing frequent forest fires.

Keywords Lateritic soils · Elevated temperature · Heating duration · Thermal degradation · Engineering properties

✉ Lekan Olatayo Afolagboye, lekan.afolagboye@eksu.edu.ng | [1]Department of Geology, Ekiti State University, Ado-Ekiti, Nigeria. [2]Department of Geology, Kwara State University, Malete, Nigeria.

1 Introduction

Approximately one-third of the intertropical zone is composed of laterite/lateritic soils [1, 2]. These soils play a vital role in engineering construction, especially in embankments and sub-grades for road pavements [3, 4]. They are also utilized as compacted clay liners in engineered landfills, in the manufacturing of compressed earth bricks, and artificial backfills [5, 6]. These residual soils, characterized by a reddish-brown color, result from the weathering of pre-existing basement or sedimentary rocks in tropical climates [7].

The impact of temperature on the engineering behavior of soil has become a prominent focus within geotechnical and geoenvironmental engineering. In recent times, numerous studies have delved into the consequences of elevated temperatures on soil properties [8, 9]. Consequently, it is crucial to direct attention toward these evolving areas, especially when clays are exposed to heat. In geotechnical engineering, soil such as residual lateritic soil may encounter elevated temperatures due to various factors, including terrestrial heat and underground water energy, advancements in energy storage within geotechnical structures, underground storage of high-level radioactive waste, and temperature fluctuations induced by fire around structures [10–12]. Additionally, soils can naturally experience high temperatures through events like wild-, forest-, or peat-fires, as well as through thermal remediation processes aimed at mitigating concentrations of hazardous organic contaminants [13, 13].

Numerous investigations have explored how elevated temperature affects the mineralogical composition, index, engineering, thermal and hydraulic properties of clays and residual soils. Findings indicate a notable impact on the geotechnical properties of both clay and residual soil resulting from thermal variations [14–18]. In the study conducted by Owoyemi and Afolagboye [14], the impact of elevated temperatures on the geotechnical properties of two lateritic soils is investigated. The research reveals alterations in Atterberg limit, MDD, UCS, and California bearing ratio (CBR) as the soils experience a range of temperatures from 25 to 200 °C. Reference [19] studied the effect of elevated temperatures on the index properties and compaction parameters of two clay types. Up to a certain temperature, an increase in MDD and a decrease in the Liquid Limit (LL) were observed. Beyond this specific temperature, minimal variations were noticed, and the soil exhibited non plastic behavior from that point onward. Reference [20] conducted a study involving the heating of black cotton soil to a temperature of 600 °C. The soil was subsequently tested for chemical analysis, particle size distribution, and compaction. The results revealed a 31% reduction in silicon oxide, while iron oxide and aluminum oxide decreased by 4% and 56%, respectively, in the thermally treated soil. These findings suggest a notable change in the soil's mineralogy.

In the investigation conducted by Owoyemi and Afolagboye [16], the researchers explored the possible modifications in the engineering and index characteristics of lateritic soils exposed to repetitive heating and cooling cycles. The results of their study indicated that the cyclic temperature fluctuations applied to the lateritic soils from Ilorin, Nigeria, had the potential to induce alterations in both index and engineering properties. Reference [21] investigated the cyclic thermal strain of a few saturated lateritic clay specimens within a temperature range of 5–70 °C, employing a thermal oedometer with an invar ring. Their findings revealed that both normally consolidated (NC) compacted and reconstituted specimens experienced an accumulation of irreversible contraction due to cyclic heating and cooling, although this occurred at a diminishing rate. For a given number of thermal cycles, the thermal strain observed in NC reconstituted specimens was approximately 30% less than that in NC compacted specimens. Previous experimental studies indicate that normally consolidated or slightly over consolidated clays may undergo irreversible deformations during heating and cooling cycles [22, 23].

Upon reviewing previous research, it is evident that the focus has predominantly been on the effect of elevated temperature not exceeding 200 °C on the engineering and index properties of residual lateritic soils. However, real-world scenarios, including wildfires, soil heated vapor extraction, incineration, or smoldering, may subject soils to temperatures surpassing 200 °C [20]. Current research on the influence of elevated temperatures on soil properties emphasizes the importance of both temperature and exposure time as critical factors. Nevertheless, previous research on the effects of elevated temperature on the properties of lateritic soils has not comprehensively investigated into the influence of exposure time.

Hence, this study primarily concentrates on investigating the impacts of elevated temperature and heating duration (exposure time) on the properties of lateritic soils originating from two distinct parent rocks. To be more precise, the lateritic soil samples undergo heating in a furnace at specified elevated temperatures for varying durations. Subsequently, they are cooled to room temperature for a series of index and geotechnical tests, encompassing Atterberg limits, compaction parameters, and unconfined compression tests.

2 Study area

Lateritic soil samples for this investigation were obtained from Ado-Ekiti, Nigeria. Ado-Ekiti has experienced rapid urbanization due to rural-to-urban migration. This growth fuels demand for new construction projects, placing increasing importance on understanding the local soil properties. Ado-Ekiti experiences a well-defined seasonal climate with distinct wet and dry periods, coupled with abundant vegetation. These factors contribute significantly to the formation of lateritic soils within the study area. Geologically, the town is situated within the Precambrian basement complex, a geological unit prevalent in Southwestern Nigeria (Fig. 1). The lateritic soils investigated in this study developed over quartzite and charnokite, which are prominent rock formations within this basement complex. The parent rock for these soils is primarily composed of quartz, feldspar, and biotite [24, 25].

3 Materials and methods

This study utilized disturbed lateritic soil samples from two distinct locations, each formed over different parent rocks—charnockite and quartzite (Fig. 1). Samples derived from quartzite were obtained from active burrow pits along New Iyin road in Ado-Ekiti, Southwestern Nigeria, where lateritic soil is commonly extracted for construction. Samples from charnockite were obtained from a road cut exposure along Old Iyin Road in Ado-EKiti. To ensure representative samples, ten bulk samples (five from each location) were collected at 10-m intervals from the lateritic horizon. These samples were carefully stored in airtight sealed polyethylene bags to preserve moisture content.

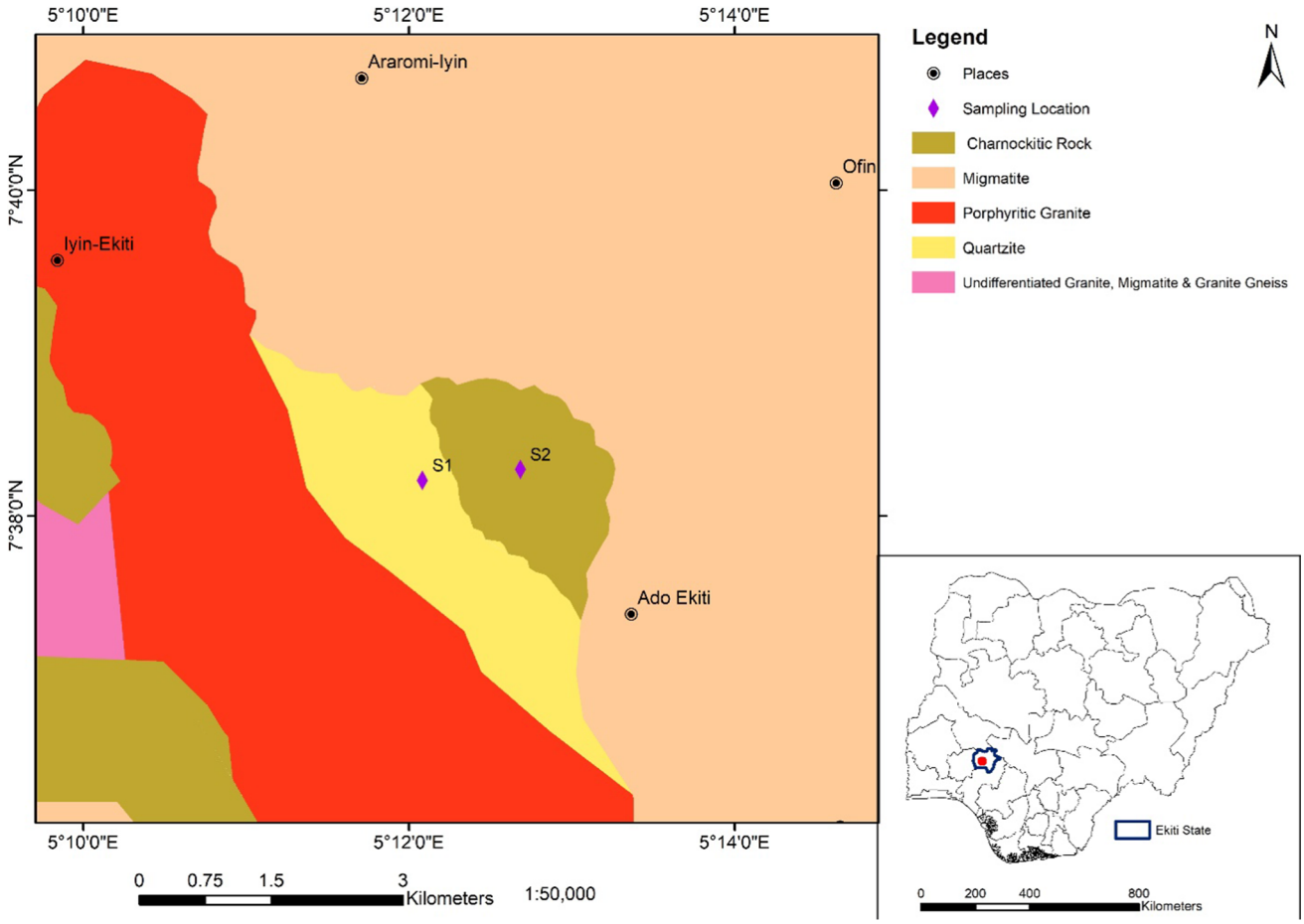


Fig. 1 Geological map of Ado-Ekiti indicating the sample locations

The collected soil samples were subjected to heating in a furnace at different temperatures (100, 200, 300, and 400 °C) for two designated durations: two hours (set A) and three hours (set B). Four samples, each weighing approximately 1 kg, were placed in separate crucibles and heated at a rate of 5 °C/minute until reaching the target temperature. Following heating, the furnace was switched off, and the crucibles containing the soil were left to cool inside the furnace to minimize thermal shock. Both natural and heated soil samples were evaluated using standard procedures to determine their index and engineering properties.

Grain size distribution was determined according to British Standard (BS) 1377 [26]. To facilitate efficient particle separation during sieve analysis, each sample was soaked in a dilute Calgon solution for 24-h with intermittent agitation, followed by wet sieving. A combination of sieve and hydrometer tests was employed to achieve a comprehensive particle size distribution profile. However, the grain size distribution was carried out only on natural samples. Consistency limits, including LL and plastic limit (PL), were determined according to BS 1377 [26] for the soil fraction passing a 425 µm sieve. Prior to testing, the sieved fractions were mixed with water and allowed to hydrate for 24 h. The liquid limit (LL) and plastic limit (PL) of the lateritic soils were determined using the fall cone device, which provides accurate and reliable measurements for both parameters.

A compaction test was performed on soil fractions that passed through a 425 µm sieve to determine the compaction parameters of the soil samples, following the guidelines specified in British Standard 1377-4. The compaction test was conducted using the standard Proctor compaction effort (SPCE). Cylindrical test specimens with diameters of roughly 10.2 cm and heights of around 11.2 cm were prepared for the compaction test.

Soil samples compacted to their Optimal Moisture Content (OMC) using the SPCE were subjected to unconfined compression tests in accordance with BS 1377-7. Cylindrical specimens, measuring 5 cm in diameter and 10 cm in height, were subjected to stress–strain controlled loading at a strain rate of 1.25 mm/min. The maximum stress recorded during this process represents the unconfined compressive strength (UCS).

Analysis of Variance (ANOVA) was employed to assess the significance of differences between the results for each geotechnical property at different temperatures and treatment durations. A two-way ANOVA test (without replication) was used when both temperature and duration were considered sources of variation. Conversely, a one-way ANOVA test (without replication) was used when only temperature was considered a source of variation. We rejected the initial assumption (null hypothesis) when the calculated F-statistic (F_{CAL}) in absolute terms was greater than the critical F-value (F_{CRIT}) and the probability value (P-value) value was less than 0.05 ($F_{CAL} > F_{CRIT}$: $P \leq 0.05$).

3.1 Properties of the lateritic soils at their natural moisture content (NMC)

Table 1 summarizes the properties of the investigated lateritic soils at their NMC. The average NMC for the charnockite derived lateritic soil (10.9%) is notably lower than that of the quartzite derived soil (15.33%), indicating a higher inherent moisture content in the latter. Both soils displayed a reddish to reddish-brown coloration upon visual examination. Figure 2 shows the grain size distribution curve of the lateritic soils.

Table 1 Properties of lateritic soils at their natural moisture content

Properties	CDLS*	QDLS*
W_L (%)	56.03	58.09
W_P (%)	28.63	33.26
I_P (%)	27.40	24.82
MDD (kg/m^3)	1777.33	1651.00
OMC (%)	15.64	12.59
UCS (kPa)	178.41	166.79
Percentage passing No 200 sieve (75 µm)	44.54	42.76
Percentage Silt	32.78	33.56
Percentage Clay	11.76	9.20
Activity	2.33	2.70
USCS	CH	MH
NMC (%)	10.94	15.33

* Average of five values; QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

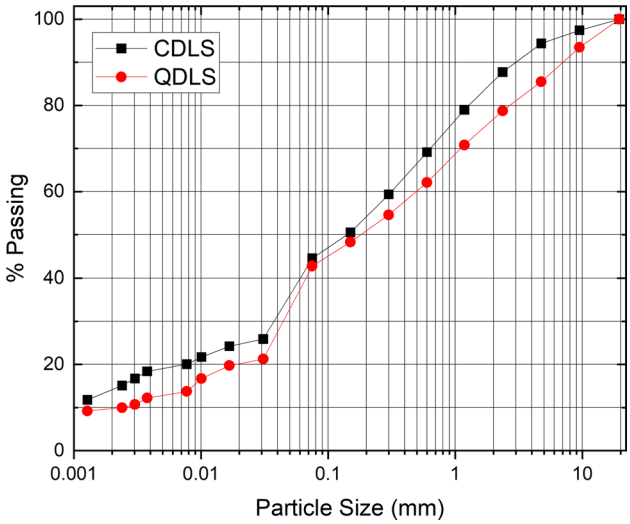


Fig. 2 Grain size distribution curve of the lateritic soils. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

Using AASHTO system, the two lateritic soils were classified as A-7-6 and A-7-5, respectively. This classification suggests that both soils, regardless of their parent rock (quartzite or charnockite), are fine-grained, silty-clayey materials. A-7-5 soils are clayey with high plasticity and poor drainage, prone to significant volume changes with moisture. A-7-6 soils have even higher plasticity and liquid limit, with greater volume change tendencies. This is further supported by their average liquid limits and plasticity indices exceeding 41% and 11%, respectively. Notably, the plasticity index exceeding 17% for all soils suggests high plasticity characteristics. Both A-7-5 and A-7-6 soils present significant challenges for construction, particularly road construction, due to their high plasticity, poor drainage characteristics, and susceptibility to considerable volume changes with moisture fluctuations. To improve their strength and performance, stabilization techniques like lime or cement treatment are necessary. The charnockite-derived lateritic soil exhibits a higher average MDD (Fig. 3) and UCS compared to the quartzite-derived soil. These variations in the properties are likely attributed to inherent differences in the mineralogical compositions and texture of the parent rock materials.

4 Results and discussion

4.1 Effect of temperature treatment and duration on atterberg limits

The liquid limit (LL) is the water content at which a soil changes from a plastic state to a liquid state, representing the minimum moisture content at which the soil can flow under its own weight. Figure 4 shows the variation in LL for both lateritic soils subjected to different heating temperatures and durations. A clear decreasing trend in LL is observed with increasing temperature, regardless of the parent rock or heating duration. The maximum LL reduction occurred at 400 °C, with values reaching as low as 31.76% and 39.61% for charnockite and quartzite-derived soils, respectively

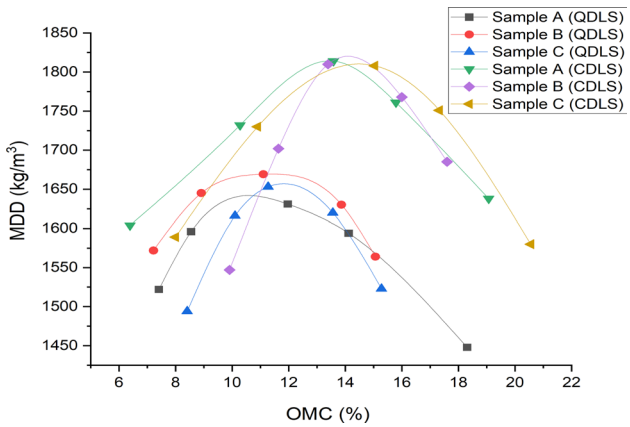


Fig. 3 Compaction curves of the of the lateritic soils. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

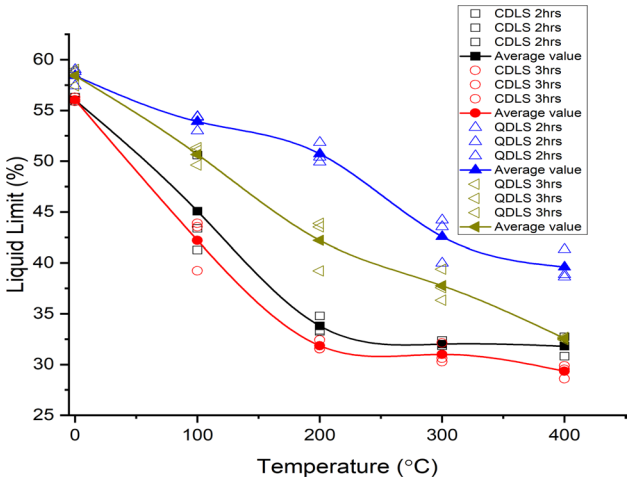


Fig. 4 Variation in LL of the lateritic soils at different heating temperature and duration. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

(heated for 2 h). This decrease was more pronounced for soils heated for longer durations (3 h) compared to those heated for 2 h. For quartzite-derived soil heated for 2 h, the LL decreased by approximately 7.73% at 100 °C, 13.21% at 200 °C, 27.12% at 300 °C, and 32.20% at 400 °C. When heated for 3 h, the LL for quartzite-derived soil decreased by approximately 13.28% at 100 °C, 27.72% at 200 °C, 35.39% at 300 °C, and 44.26% at 400 °C. Similarly, for charnockite-derived soil heated for 2 h, the LL decreased by approximately 19.56% at 100 °C, 39.66% at 200 °C, 42.87% at 300 °C, and 43.26% at 400 °C. When heated for 3 h, the LL for charnockite-derived soil decreased by approximately 24.64% at 100 °C, 43.17% at 200 °C, 44.64% at 300 °C, and 47.65% at 400 °C.

This trend can be attributed to several factors, including dehydration altering the clay mineral composition, the presence of gibbsite and allophane, a decrease in the soil's specific surface area, particle clumping, and dehydration-induced breakdown of soil particles [14, 27]. Elevated temperatures often lead to a reduction in the specific surface area of soil particles due to particle clumping, breakdown of soil fabric, and alterations in interparticle contacts, as noted by these authors. These changes contribute to the reduction or disappearance of the diffuse double layer, diminishing the soil's ability to retain water and resulting in the observed trends. The LL values of both soils were consistently higher across all heating temperatures when subjected to a 2-h heating duration compared to a 3-h duration. The more significant decrease in liquid limit observed after a 3-h heating period may be linked to prolonged changes in clay mineralogy resulting from dehydration and the other aforementioned factors.

The results of the one-way ANOVA conducted on soil properties for both lateritic soils are summarized in Table 2. Interestingly, while the figures visually showed a clear trend, the one-way ANOVA results (Table 2) suggested no statistically significant impact of temperature on the liquid limit for either soil type at both durations (2 and 3 h). For example, when examining the liquid limit test results for a 2-h duration, the analysis indicates that temperature did not have a significant effect on charnockite-derived lateritic soil ($F_{CAL} = 5.1132 < F_{CRIT} = 5.3177$) and quartzite-derived lateritic soil ($F_{CAL} = 4.5459 < F_{CRIT} = 5.3177$). This finding aligns with previous studies by [14, 18] that also reported a lack of statistically significant effect of temperature on the LL of residual soils. The one-way ANOVA results showed no statistically significant impact of temperature on the liquid limit for either soil type at both durations. This could be due to the variability within the temperature treatments being insufficient to produce a statistically discernible effect on the liquid limit when considered independently.

The results of the two-way ANOVA conducted on soil properties for both lateritic soils are summarized in Table 3. The two-way ANOVA results (Table 3), which considers the combined effects of temperature and duration, indicates a significant influence on LL for both soils. This suggests that while temperature alone may not significantly affect the LL, the combination of temperature and duration has a notable impact on this soil property. In order words, the combined effect of these factors is likely more impactful than either factor alone, leading to the significant results observed in the two-way ANOVA.

The plastic limit (PL) is the water content at which a soil changes from a semi-solid state to a plastic state. Figure 5 shows the PL of lateritic soils derived from charnokite and quartzite at various heating temperatures and durations. Similar to the LL, the PL of both soils exhibited a decreasing trend with increasing temperature across all heating durations (Fig. 5). This decrease was more pronounced for soils heated for longer durations (3 h) compared to those heated for 2 h.

Table 2 One-way ANOVA results for the properties of the lateritic soils

Heat Duration	Property	Soil type	Source of variation	Degree of freedom	F_{CAL}	P-value	F_{CRIT}	Remarks
2 h	Liquid Limit	Charnokite	Temp	1	5.1132	0.0536	5.3177	NS
		Quartzite		8	4.5459	0.0656	5.3177	NS
	Plastic Limit	Charnokite	Temp	1	6.2216	0.0373	5.3177	Significant
		Quartzite		8	5.7339	0.0435	5.3177	Significant
	Plasticity Index	Charnokite	Temp	1	6.7748	0.0315	5.3177	Significant
		Quartzite		8	6.5775	0.0334	5.3177	Significant
	MDD	Charnokite	Temp	1	324.3456	0.0000	5.3177	Significant
		Quartzite		8	368.0438	0.0000	5.3177	Significant
	OMC	Charnokite	Temp	1	6.8977	0.0303	5.3177	Significant
		Quartzite		8	7.0349	0.0291	5.3177	Significant
	UCS	Charnokite	Temp	1	0.6637	0.4388	5.3177	NS
		Quartzite		8	0.5252	0.4893	5.3177	NS
3 h	Liquid Limit	Charnokite	Temp	1	5.2166	0.0517	5.3177	NS
		Quartzite		8	4.8261	0.0593	5.3177	NS
	Plastic Limit	Charnokite	Temp	1	6.3094	0.0363	5.3177	Significant
		Quartzite		8	5.9646	0.0404	5.3177	Significant
	Plasticity Index	Charnokite	Temp	1	5.2166	0.0517	5.3177	NS
		Quartzite		8	6.6693	0.0325	5.3177	Significant
	MDD	Charnokite	Temp	1	261.157	0.0000	5.3177	Significant
		Quartzite		8	349.841	0.0000	5.3177	Significant
	OMC	Charnokite	Temp	1	6.8577	0.0307	5.3177	Significant
		Quartzite		8	7.0037	0.0294	5.3177	Significant
	UCS	Charnokite	Temp	1	0.6909	0.4300	5.3177	NS
		Quartzite		8	0.6367	0.4480	5.3177	NS

NS: Not significant; MDD: Maximum Dry Density; OMC: Optimum Moisture Content; UCS: Unconfined Compressive Strength; Temp: Temperature

The most pronounced decrease in PL occurred between 100 °C and 200 °C, particularly for charnockite-derived lateritic soil, and when the heating duration was 3 h in quartzite-derived lateritic soil. However, the rate of decrease became minimal beyond 200 °C. The most pronounced decrease in PL occurred between 100 °C and 200 °C, particularly for charnockite-derived lateritic soil and when the heating duration was 3 h in quartzite-derived lateritic soil. The rate of decrease in, in charnokite-derived lateritic soil became minimal beyond 200 °C. For quartzite-derived soil heated for 2 h, the PL decreased by approximately 5.83% at 100 °C, 7.87% at 200 °C, 21.64% at 300 °C, and 22.57% at 400 °C. When heated for 3 h, the PL for quartzite-derived soil decreased by approximately 12.89% at 100 °C, 29.10% at 200 °C, 29.20% at 300 °C, and 36.02% at 400 °C. Similarly, for charnockite-derived soil heated for 2 h, the PL decreased by approximately 6.78% at 100 °C, 26.88% at 200 °C, 27.69% at 300 °C, and 26.89% at 400 °C. When heated for 3 h, the PL for charnockite-derived soil decreased by approximately 14.21% at 100 °C, 30.55% at 200 °C, 33.03% at 300 °C, and 32.30% at 400 °C. The decrease in plastic limits with increasing temperature can be ascribed to the fragmentation of soil particles, which can also cause changes in the overall microscopic structure and mineralogy of the soil [28].

The one-way ANOVA results (Table 2) confirmed a statistically significant effect of temperature treatment on the plastic limit for either soil type at both durations (2 and 3 h). For instance, in the case of the plastic limit test results for a 3-h duration, the analysis shows that temperature had significant effects on charnokite-derived lateritic soil ($F_{CAL} = 6.3094 > F_{CRIT} = 5.3177$) and quartzite-derived lateritic soil ($F_{CAL} = 5.9646 > F_{CRIT} = 5.3177$). This suggests that temperature alone is a dominant factor affecting the plastic limit. The significant effect observed in the one-way ANOVA implies that the changes in temperature result in consistent and substantial alterations in the plastic limit, regardless of the duration of exposure. This finding aligns with observations from previous research [14, 18]. Similarly, the two-way ANOVA results (Table 3) corroborated this observation, indicating a significant impact of both temperature and duration on the plastic limit of both soils. This suggests that the interaction between temperature and duration plays a crucial

Table 3 Results from a two-way ANOVA for the properties of the lateritic soils

Property	Soil type	Source of variation	Degree of freedom	F_{CAL}	P- value	F_{CRIT}	Remarks
Liquid Limit	Charnokite	Temperature	4	356.3648	2.34E-05	6.3882	Significant
		Duration of heating	1	10.2330	0.0329	7.7086	Significant
	Quartzite	Temperature	4	29.3054	0.0032	6.3882	Significant
		Duration of heating	1	10.0784	0.0337	7.7086	Significant
Plastic Limit	Charnokite	Temperature	4	98.6404	0.0003	6.3882	Significant
		Duration of heating	1	12.2985	0.0247	7.7086	Significant
	Quartzite	Temperature	4	9.0363	0.0278	6.3882	Significant
		Duration of heating	1	7.7242	0.0499	7.7086	Significant
Plasticity Index	Charnokite	Temperature	4	483.3760	0.0000	6.3882	Significant
		Duration of heating	1	1.9938	0.2308	7.7086	NS
	Quartzite	Temperature	4	108.4843	0.0002	6.3882	Significant
		Duration of heating	1	8.6235	0.0425	7.7086	Significant
MDD	Charnokite	Temperature	4	22.4771	0.0053	6.3882	Significant
		Duration of heating	1	8.1234	0.0464	7.7086	Significant
	Quartzite	Temperature	4	109.5336	0.0002	6.3882	Significant
		Duration of heating	1	8.3594	0.0445	7.7086	Significant
OMC	Charnokite	Temperature	4	16.9268	0.0090	6.3882	Significant
		Duration of heating	1	7.2600	0.0544	7.7086	NS
	Quartzite	Temperature	4	8.4169	0.0314	6.3882	Significant
		Duration of heating	1	3.2194	0.1472	7.7086	NS
UCS	Charnokite	Temperature	4	992.2099	0.0000	6.3882	Significant
		Duration of heating	1	4.0805	0.1135	7.7086	NS
	Quartzite	Temperature	4	27.7171	0.0036	6.3882	Significant
		Duration of heating	1	6.1516	0.0682	7.7086	NS

NS: Not significant; MDD: Maximum Dry Density; OMC: Optimum Moisture Content; UCS: Unconfined Compressive Strength

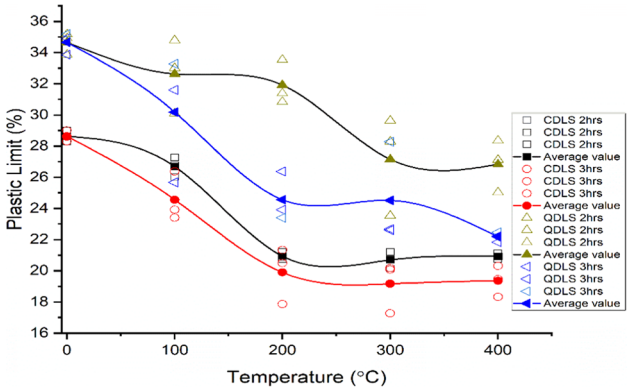


Fig. 5 Variation in plastic limit of the lateritic soils at different heating temperature and duration. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

role in influencing the plastic limit. The combined effect of these factors is likely more impactful than either factor alone, leading to the significant results observed in the two-way ANOVA.

The plasticity index (PI), which reflects the soil's potential range of behavior in plastic states, followed a decreasing trend with increasing temperature and duration for both soils (Fig. 6). This trend reflects the combined reductions observed in LL and PL. The minimum PI values were recorded at 400 °C, reaching as low as 10.87% and 12.77% for charnockite and quartzite-derived lateritic soils, respectively, with a 2-h heating duration. For quartzite-derived soil heated for 2 h, the PI decreased by approximately 13.44% at 100 °C, 23.52% at 200 °C, 37.22% at 300 °C, and 48.05% at 400 °C. When heated for 3 h, the PI for quartzite-derived soil decreased by approximately 16.63% at 100 °C, 28.17% at 200 °C, 46.09% at 300 °C, and 57.68% at 400 °C. Similarly, for charnockite-derived soil heated for 2 h, the PI decreased by approximately

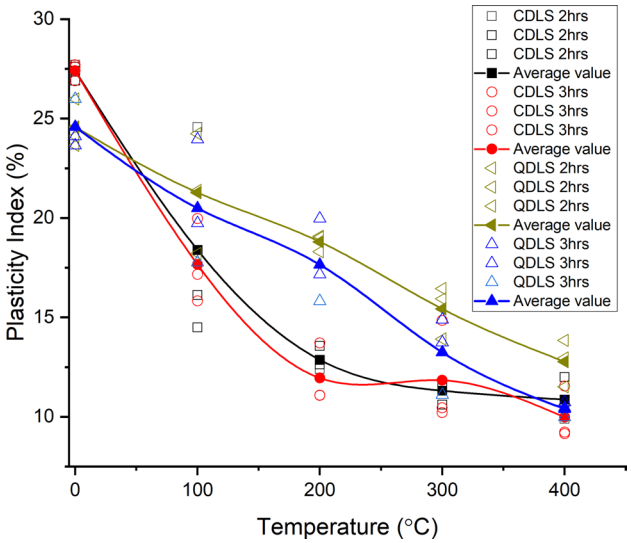


Fig. 6 Variation in PI of the lateritic soils at different heating temperature and duration. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

32.90% at 100 °C, 53.03% at 200 °C, 58.72% at 300 °C, and 60.32% at 400 °C. When heated for 3 h, the PI for charnockite-derived soil decreased by approximately 35.53% at 100 °C, 56.36% at 200 °C, 56.77% at 300 °C, and 63.56% at 400 °C. A possible explanation for this decrease is the de-hydroxylation of clay minerals at higher temperatures, leading to particle assembly and sintering [27]. Dehydration can induce structural changes in clay minerals, particularly in lateritic soils that are rich in kaolinite. When exposed to elevated temperatures, the loss of bound water in these minerals results in alterations to their crystal structure. This decrease was generally more pronounced for soils heated for 3 h compared to those heated for 2 h except in charnokite-derived lateritic soil samples at 300 °C, where the plasticity index was slightly higher with a 3-h heating duration.

The one-way ANOVA results (Table 2) reveal a statistically significant effect of temperature treatment on the plasticity index for both soils at the 2- and 3-h durations ($_{FCAL} > F_{CRIT}$), except for charnokite-derived lateritic soil heated for 3 h. For instance, at the 2-h duration, the analysis shows significant effects of temperature on charnokite-derived lateritic soil ($_{FCAL} = 6.7748 > F_{CRIT} = 5.3177$) and quartzite-derived lateritic soil ($F_{CAL} = 6.5775 > F_{CRIT} = 5.3177$).

This indicates that temperature alone significantly influences the plasticity index, causing consistent and substantial changes. However, an exception was noted for charnokite-derived soil at the 3-h duration, where the impact of temperature was insignificant. This could be due to the soil reaching a thermal equilibrium, where its plasticity stabilizes, making additional exposure to temperature changes less impactful. This finding is consistent with previous studies [14, 18]. However, it contradicts the observations of [15] who reported no significant impact of drying temperature on the PI of marine clay.

The two-way ANOVA results (Table 3) indicate varying effects of temperature and duration on PI. While temperature had a significant effect ($p < 0.05$) on PI for both soils, duration only significantly affected PI in quartzite-derived lateritic soil ($F_{CAL} > F_{CRIT}$). The significant effect of temperature on PI for both soils suggests that temperature plays a dominant role in altering the soil's plasticity characteristics. However, significant effect of duration on PI in quartzite-derived lateritic soil, but not in charnockite-derived soil, suggests that quartzite-derived soil is more sensitive to prolonged heating. This sensitivity might be due to differences in mineral composition and thermal stability between the two soil types.

4.2 Plasticity characteristics of the soils

Figure 7 shows the Unified Soil Classification System (USCS) classification of the investigated soil fractions based on the Casagrande plasticity chart. The natural, unheated lateritic soil derived from charnockite is classified as CH (inorganic clay of high compressibility), whereas the quartzite-derived soil falls under the MH classification (inorganic silt of high compressibility). These inherent differences in plasticity characteristics likely stem from variations in the degree of weathering experienced by the parent rock and the mineralogical composition.

The USCS classification and, consequently, the plasticity level of the soils noticeably changed upon exposure to elevated temperatures and varying durations. In the case of charnockite-derived soil (Fig. 7a), the plasticity classification shifted from CH (inorganic clay of high compressibility) to CL (inorganic clay of intermediate compressibility) at 100 °C

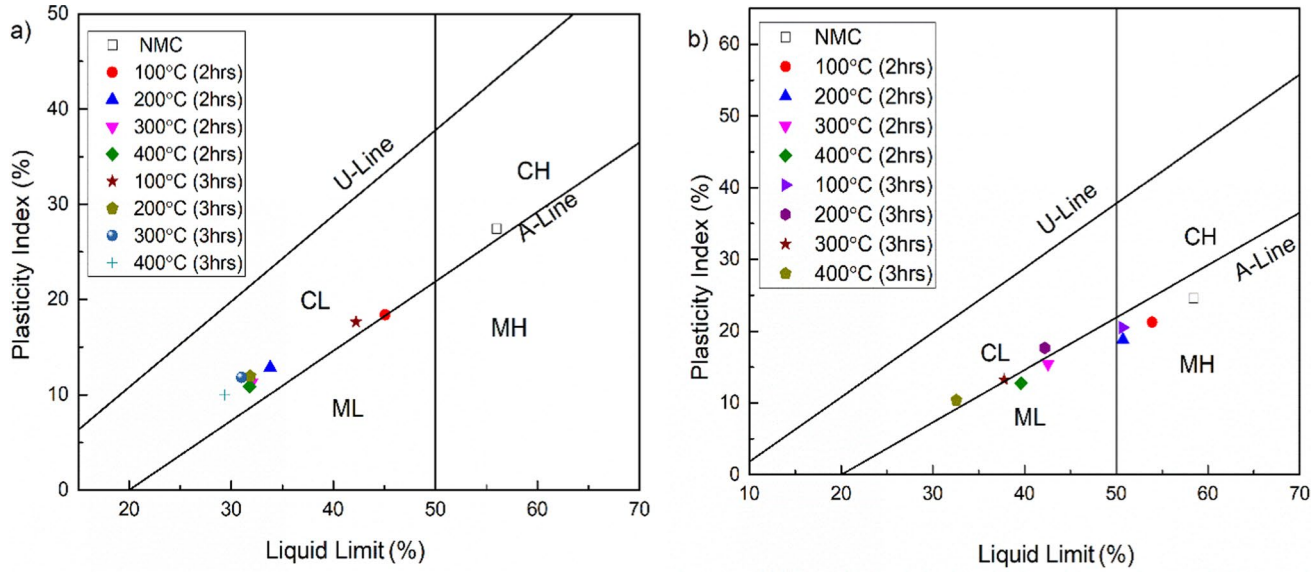


Fig. 7 Casagrande plasticity chart illustrating the changes in plasticity for lateritic soils: **a**) Lateritic soil derived from charnockite **b**) Lateritic soil derived from quartzite

for both heating durations (2 and 3 h). However, a closer examination of the data points on the Casagrande chart (representing samples heated at 100 °C for 2 and 3 h) reveals a distinct trend towards lower plasticity with increasing heating duration. This suggests that even within the CL classification, the soil becomes progressively less plastic with extended heating at 100 °C. This could be attributed to the initiation of clay mineral dehydroxylation at this temperature, leading to a decrease in water adsorption capacity, a key factor influencing plasticity [29]. Additionally, high temperatures could promote particle aggregation and sintering phenomena, further reducing the soil's overall plasticity [30]. For charnockite-derived lateritic soil heated at higher temperatures (200–400 °C) for both durations, the USCS classification shifted to CL (inorganic clay of low compressibility). Samples heated for 3 h consistently exhibited lower plasticity compared to those heated for 2 h at the same temperature.

The response of quartzite-derived lateritic soil (Fig. 7b) to the thermal treatment differs slightly. While the USCS classification remains MH (inorganic silt of high compressibility) for samples heated at 100 °C for both durations, a relative shift in data points on the Casagrande chart suggests a decrease in plasticity with increasing temperature. This aligns with the observations for charnockite-derived lateritic soil. For samples heated for 2 h at temperatures exceeding 100 °C, the plasticity characteristics changed to MI (inorganic silt of intermediate compressibility). This suggests a potential transformation from a more plastic to a less plastic silt fraction due to the thermal treatment. Intriguingly, samples heated for 3 h at temperatures ranging from 200 °C to 400 °C exhibited a shift in classification from MH (inorganic silt of high compressibility) to CL (inorganic clay of low compressibility). This could be due to temperature-induced transformations within the soil particles, potentially leading to the formation of new clay minerals with different plasticity characteristics. The sample heated for 400 °C for 3 h displayed the lowest plasticity within the CL category, suggesting a more pronounced effect of extended heating at the highest temperature.

4.3 Effect of temperature treatment and duration on compaction characteristics

The maximum dry density (MDD) is the highest density that a soil can achieve when compacted at its optimum moisture content (OMC). Figure 8 presents the response of MDD in both lateritic soils to variations in heating temperature and duration. A consistent increase in MDD is observed for both soils with increasing temperature, reaching peak values at 400 °C for both the 2-h and 3-h heating durations (Fig. 8a and b). For example, the MDD of charnockite-derived lateritic soil increased from its natural state (1777.33 kN/m^3) to 2144.33 kN/m^3 and 2316.89 kN/m^3 for the 2-h and 3-h durations at 400 °C, respectively. This result is in line with the findings reported by Villar and Lloret, and Abu-Zreig et al. [31, 32]. For quartzite-derived soil heated for 2 h, the MDD increased by approximately 1.05% at 100 °C, 2.42% at 200 °C, 6.76% at 300 °C, and 11.87% at 400 °C. When heated for 3 h, the MDD for quartzite-derived soil increased by approximately 1.96% at 100 °C, 4.14% at 200 °C, 7.97% at 300 °C, and 14.66% at 400 °C. Similarly, for charnockite-derived soil heated for 2 h,

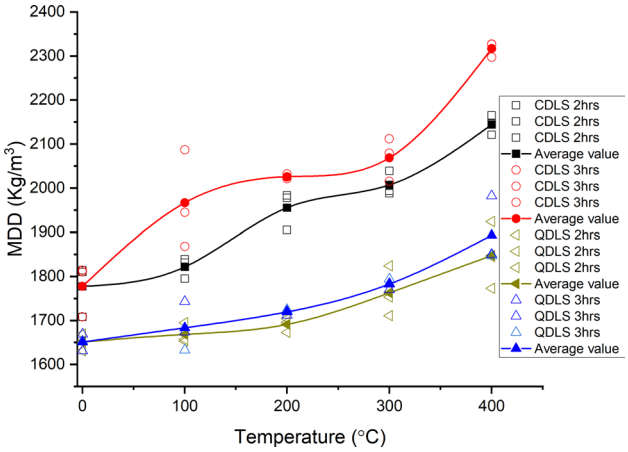


Fig. 8 Variation in maximum dry density of the lateritic soils at different heating temperature and duration. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

the MDD increased by approximately 2.50% at 100 °C, 10.04% at 200 °C, 12.93% at 300 °C, and 20.66% at 400 °C. When heated for 3 h, the MDD for charnockite-derived soil increased by approximately 10.66% at 100 °C, 14.02% at 200 °C, 16.38% at 300 °C, and 30.39% at 400 °C.

The observed increase in MDD can be attributed to several factors related to thermal effects on soil properties. Dehydration and potential physicochemical transformations at elevated temperatures may contribute to a denser packing arrangement of soil particles [18, 31]. Furthermore, a decrease in the number of micropores and the formation of more homogeneously compacted particles during the compaction process at higher temperatures could also explain the MDD increase, as suggested by Chen et al. [10].

Interestingly, the 3-h heating duration generally resulted in higher average MDD values compared to the 2-h duration across all temperatures for both soils. This might be due to a more pronounced transformation of the lateritic soils into a more cohesionless state due to sintering at higher temperatures with extended heating duration. The higher MDD of charnockite-derived soil at all temperature of thermal treatment and duration indicates that it can be compacted to a denser state, resulting in a greater load-bearing capacity. This characteristic makes it particularly suitable for supporting the heavy loads typically experienced in road construction.

The one-way ANOVA results in Table 2 confirm a statistically significant influence of temperature treatment on MDD for both soils, regardless of the duration ($F_{CAL} > F_{CRIT}$). For instance, in the case of the MDD results for a 2-h duration, the analysis shows significant effects of temperature on charnokite-derived lateritic soil ($F_{CAL} = 324.3456 > F_{CRIT} = 5.3177$) and quartzite-derived lateritic soil ($F_{CAL} = 368.0438 > F_{CRIT} = 5.3177$). This suggests that temperature is a dominant factor affecting the MDD. The significant effect observed in the one-way ANOVA indicates that changes in temperature consistently and substantially alter the MDD, regardless of the duration of exposure. Similar conclusions were drawn by Nayak and Preetham, and Gadzama et al. [15, 18]. In their respective studies, indicating a statistically significant effect of temperature on the MDD of the residual soils examined. Furthermore, the two-way ANOVA results (Table 3) indicate that both temperature and duration of treatment significantly affect MDD ($F_{CAL} > F_{CRIT}$) for both soils. This indicates that the interaction between temperature and duration is critical in affecting the MDD. The combined influence of these factors is probably more significant than either factor alone, resulting in the notable outcomes observed in the two-way ANOVA.

The optimum moisture content (OMC) is the water content at which a soil can be compacted to achieve its MDD. Figure 9 shows the impact of temperature treatment and duration on the OMC of the lateritic soils. Although the OMC at NMC was consistently higher than that of heated samples, the reduction trend with increasing temperature varied across soil types and heating durations. For charnockite-derived lateritic soil, OMC decreased from 16.05% in its natural state to 14.38% at 100 °C (a decrease of approximately 10.40%), 13.33% at 200 °C (a decrease of approximately 16.92%) and reached its lowest value of 13.33% at 200 °C for the 2-h heating duration. This was followed by an increase to 13.77% at 300 °C (a decrease of approximately 14.21%) and further to 13.89% at 400 °C (a decrease of approximately 13.45%). For the 3-h duration, the OMC decreased from 16.05% to 15.32% at 100 °C (a decrease of approximately 4.55%), 14.38% at 200 °C (a decrease of approximately 10.40%), 14.24% at 300 °C (a decrease of approximately 11.28%), and 14.14% at 400 °C (a decrease of approximately 11.89%). For quartzite-derived lateritic soil, the OMC decreased from 13.71% in its natural state to 12.77% at 100 °C (a decrease of approximately 6.86%), 12.61% at 200 °C (a decrease of approximately 8.02%) and reached its lowest value of 11.50% at 300 °C (a decrease of approximately 16.12%) for the 2-h duration. This was followed by a slight increase to 11.65% at 400 °C (a decrease of approximately 15.02%). For the 3-h duration, the

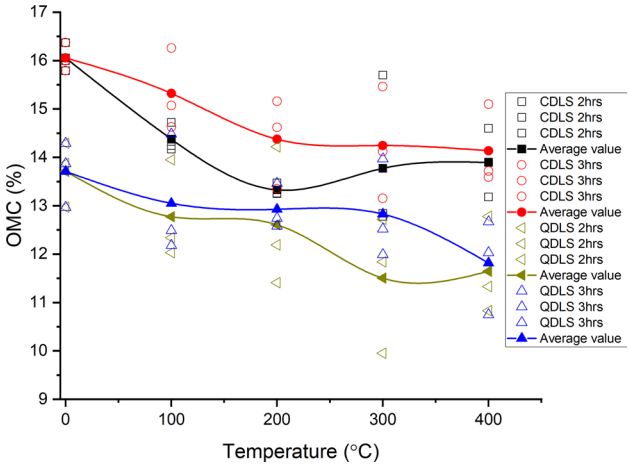


Fig. 9 Variation in optimum moisture content of the lateritic soils at different heating temperature and duration. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

OMC decreased from 13.71% to 13.05% at 100 °C (a decrease of approximately 4.81%), 12.93% at 200 °C (a decrease of approximately 5.70%), 12.83% at 300 °C (a decrease of approximately 6.41%), and 11.82% at 400 °C (a decrease of approximately 13.78%). Similar to charnockite-derived soil, the OMC values for quartzite were consistently higher with the 3-h heating duration across all temperatures.

The decrease in OMC observed at higher temperatures may be attributed to improvements in soil characteristics, potentially leading to a decrease in the diffuse double layer surrounding clay particles, subsequently affecting their water holding capacity [14]. Another possible explanation for the variability in OMC could be linked to variations in the hydromechanical properties of the soils under thermal treatment, as reported in various studies [31]. The one-way ANOVA results (Table 2) indicate a statistically significant effect of temperature treatment on OMC for both soils at the 2-h and 3-h durations. For instance, in the case of the OMC results for a 2-h duration, the analysis shows significant effects of temperature on charnokite-derived lateritic soil ($F_{CAL} = 6.897 > F_{CRIT} = 5.3177$) and quartzite-derived lateritic soil ($F_{CAL} = 7.0349 > F_{CRIT} = 5.3177$). Just like with MDD, temperature has a strong impact on the OMC. The one-way ANOVA results show that changes in temperature consistently and significantly affect the OMC, no matter how long the exposure. Similar conclusions were drawn by [15, 18] in their study, indicating a statistically significant effect of temperature on the compaction parameter of the residual soils examined.

However, the two-way ANOVA results in Table 3 reveal varying effects of temperature and duration on OMC. The analysis suggests that only temperature, and not duration, significantly impacts OMC for both soils ($F_{CAL} > F_{CRIT}$) based on the source of variation being temperature. This suggests that the OMC of the two soils may not be sensitive to prolonged heating.

4.4 Effect of temperature treatment and duration on UCS

The unconfined compressive strength (UCS) is the highest axial compressive stress a soil sample can withstand without lateral support. It measures the soil's ability to resist compression. Figure 10 show selected stress–strain curves of the lateritic soils. The peak of these curves represents the maximum stress, which occurs at the strain point where the material fails. This peak stress, known as the UCS, is a key parameter in understanding the material's resistance to compression. Figure 11 presents the effects of temperature variation and treatment duration on the UCS of lateritic soils derived from charnockite and quartzite. The results, presented in Fig. 11a and b, reveal a consistent trend of decreasing UCS (average value) with increasing temperature for both soil types, regardless of the heating duration (2 or 3 h). Compared to their natural state (178.41 kPa for charnokite derived lateritic soil and 166.79 kPa for quartzite derived lateritic soil), UCS values exhibit a significant decrease at 400 °C, reaching minimum values of 126.85 kPa (charnokite derived lateritic soil, 2 h) and 123.48 kPa (quartzite derived lateritic soil, 2 h).

For charnockite-derived lateritic soil, UCS decreased from 178.41 kPa in its natural state to 139.35 kPa at 100 °C (a decrease of approximately 21.89%), 132.59 kN/m^2 at 200 °C (a decrease of approximately 25.67%), 132.27 kPa at 300 °C (a decrease of approximately 25.87%), and 126.85 kPa at 400 °C (a decrease of approximately 28.91%) for the 2-h heating duration. For the 3-h duration, UCS decreased from 178.41 kPa to 138.92 kPa at 100 °C (a decrease of approximately 22.15%), 131.98 kPa at 200 °C (a decrease of approximately 25.99%), 130.57 kPa at 300 °C (a decrease of approximately 26.78%), and 123.48 kPa at 400 °C (a decrease of approximately 30.81%). For quartzite-derived lateritic soil, UCS decreased

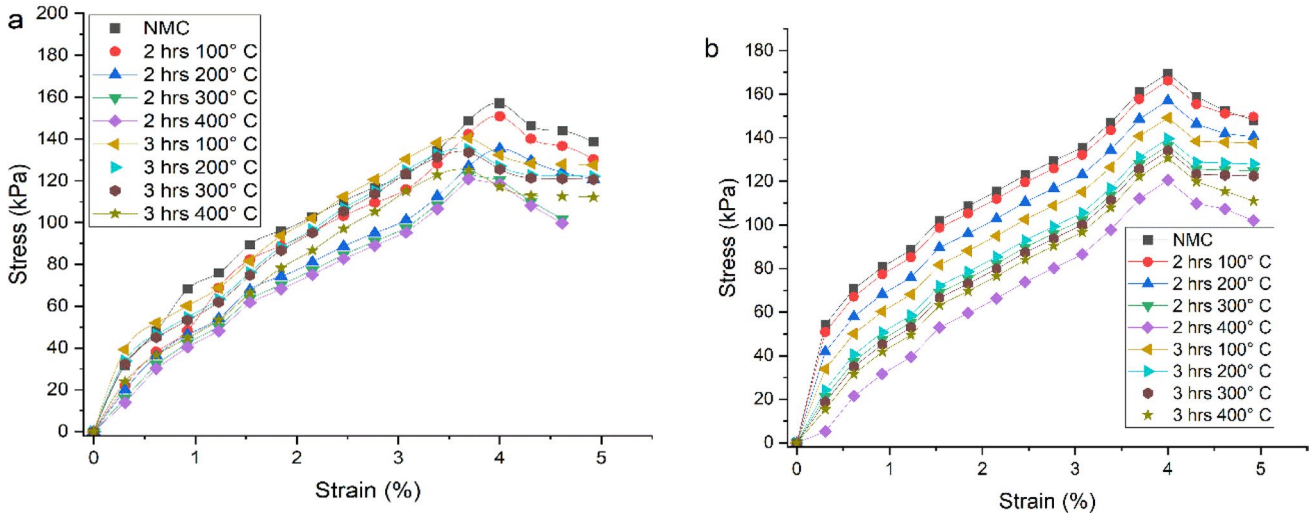


Fig. 10 Stress–strain plot of soil specimens **a** charnokite derived lateritic soil **b** Quartzite derived lateritic soil

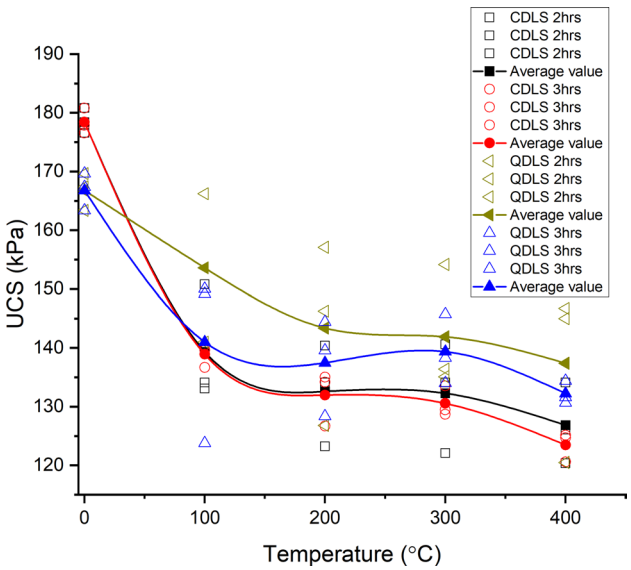


Fig. 11 Variation in UCS of the lateritic soils at different heating temperature and duration. QDLS: Quartzite derived lateritic soil; CDLS: Charnokite derived lateritic soil

from 166.79 kPa in its natural state to 153.60 kPa at 100 °C (a decrease of approximately 7.90%), 143.38 kPa at 200 °C (a decrease of approximately 14.05%), 141.90 kPa at 300 °C (a decrease of approximately 14.90%), and 137.41 kPa at 400 °C (a decrease of approximately 17.60%) for the 2-h heating duration. For the 3-h duration, UCS decreased from 166.79 kPa to 141.00 kPa at 100 °C (a decrease of approximately 15.48%), 137.48 kPa at 200 °C (a decrease of approximately 17.58%), 139.36 kPa at 300 °C (a decrease of approximately 16.45%), and 132.24 kPa at 400 °C (a decrease of approximately 20.73%).

This observation aligns with findings reported by Attah and Etim [14]. The reduction in UCS can be credited to the thermal alteration of the soil structure. As temperature increases, the residual soils undergo changes that lead to increased porosity and micro-crack formation, likely due to dihydroxylation processes [33]. The heating temperatures may have disrupted the clay particle structure and mineral composition that initially formed during deposition. This effect became evident when coarser grains were produced due to a decrease in clay content, leading to a subsequent reduction in the plasticity of both soils. The results also suggest that a longer heating duration (3 h) generally leads to lower UCS values compared to the 2-h duration across all temperatures, except for charnokite derived lateritic soil at 100 °C. This exception might be due to the initial stages of sintering at this temperature, leading to minimal changes in the soil structure for charnokite derived lateritic soil within this short timeframe [33]. At higher temperatures, however, prolonged heating likely accelerates the creation of porosity and micro-cracks, resulting in a more pronounced decrease in UCS. The higher

UCS values of charnockite-derived soil suggest it has a greater resistance to compressive stress, enhancing its stability and durability under traffic loads. This increased stability reduces the likelihood of deformation and failure over time, contributing to the overall integrity of road infrastructure.

The one-way ANOVA test results presented in Table 2 indicate a statistically insignificant effect of temperature treatment on UCS for both soils at both durations. For example, the F_{CAL} for charnokite derived soils at 2 h ($F_{CAL} = 0.6637$) is considerably lower than the critical F-value ($F_{CRIT} = 5.3177$), suggesting no statistically significant impact of temperature on UCS. This could be because the temperature variations were not large enough to create a statistically significant impact on the liquid limit when analyzed on their own. This aligns with the findings of [14] who also reported similar insignificant effects.

The two-way ANOVA results in Table 3 present a slightly different perspective. This test, which considers the combined effects of temperature and duration, reveals that temperature has a significant influence on UCS ($F_{CAL} > F_{CRIT}$) for both quartzite and charnokite-derived soils. However, the effect of heating duration appears to be less pronounced. This suggests that while temperature plays a dominant role in altering UCS, the duration of heating may have a more subtle influence, depending on the specific temperature and soil type.

5 Conclusion

The study investigated the impact of elevated temperature and treatment duration on lateritic soils, revealing the following significant variations in their index and engineering properties:

1. Higher temperatures resulted in a reduction of plasticity for both lateritic soils derived from different parent rocks. For instance, the plasticity index decreased by up to 63.56% for charnockite-derived soil and 57.68% for quartzite-derived soil at 400 °C for 3 h.
2. Elevated temperatures led to changes in compaction characteristics. Specifically, the maximum dry density increased by up to 30.39% for charnockite-derived soil and 14.66% for quartzite-derived soil at 400 °C for 3 h. The optimum moisture content decreased by approximately 11.89% for charnockite-derived soil and 13.78% for quartzite-derived soil at 400 °C for 3 h.
3. Higher temperatures caused a decrease in UCS. For example, UCS decreased by up to 30.81% for charnockite-derived soil and 20.73% for quartzite-derived soil at 400 °C for 3 h.
4. The duration of heating also influenced soil properties. Longer durations generally resulted in more pronounced changes. For instance, a 3-h exposure at 200 °C had a more significant impact on the reduction of plasticity and UCS compared to a 2-h exposure.
5. Statistical analyses confirmed that temperature was the dominant factor affecting most soil properties, while the effect of duration, though present, was less pronounced.
6. The shift from high to low compressibility with increasing temperature and duration suggests that thermal treatment can effectively modify these soil properties. This was evidenced by a change from CH (high compressibility) to MH (medium compressibility) classifications.
7. It is important to consider temperature and exposure time when evaluating the behavior of lateritic soils in tropical regions, which often experience forest fires. Future research could investigate the mineralogical transformations occurring within lateritic soils at elevated temperatures using techniques such as thermogravimetric analysis (TGA).

Author contributions Lekan Olatayo Afolagboye: Conceived and performed the experiments; Analyzed and interpreted the data; Wrote and edit the paper. Olubunmi Oluwadare Owoyemi: Wrote the Paper and Analyzed and interpreted the data, performed the statistical analysis. Yusuf Ademola Abdu-Raheem: performed the experiment and interpreted the data; Wrote the paper. Aderemi Sunday Adeoye: performed the experiments and edit the paper.

Data availability They are included in the article.

Declarations

Competing interests The authors declare no competing interests.

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