Experimental investigation on the effects of elevated temperature on geotechnical behaviour of tropical residual soils

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Abstract

The engineering performance of soil after exposure to temperature is increasingly important in geotechnical and geoenvironmental engineering. Most thermal remediation of soil concentrates more on the remediation outcome and eliminates the effects temperature will have on the engineering properties of the soil itself. This paper presents the results of laboratory study conducted on two lateritic soils to investigate effect of elevated temperature difference on their geotechnical properties. The soils were classified as A-7-6 (8) and A-7-5 (4) based on the AASHTO soil classification system. After subjecting the soil samples to elevated temperatures (25, 50, 100, 150 and 200 °C), tests such as Atterberg limit, compaction, California bearing ratio (CBR), unconfined compressive strength (UCS) and scanning electron microscopy were carried on the samples. The results showed a decrease in Atterberg limit and increase in maximum dry density. The peak CBR for both the soils was obtained at 150 °C. The UCS increased with curing time but decreased with increased pre-heat temperature for both soils. The microanalysis result portrayed changes in morphological structure of fabrics which indicates a breakdown in the microstructural properties of the soil due to temperature variation. Generally, the statistical analysis of variance showed that temperature has significant effect on the geotechnical properties of residual soils.

Keywords Temperature · Atterberg limits · Compaction · Lateritic soil · Scanning electron microscope · Statistical analysis

1 Introduction

Temperature is a fundamental property that has great impact on engineering properties of soils [1]. According to Paaswell [2], the permeability, strength, expansibility of clayey soil change under different temperatures. Temperature effect on the engineering performance of soil is an increasingly important area in geotechnical and geoenvironmental engineering. This is due to the increase in infrastructural development of large underground facilities such as buried high-voltage cables [3], oil and gas pipelines [4] and radioactive waste disposal [5]. Soil surrounding these infrastructures exposed to elevated temperature for a long period of time could suffer some effect in terms of hydraulic and mechanical properties [6].

Soil used in engineering infrastructures could also be exposed to high temperatures naturally through wild forest fires or through thermal remediation processes [7]. These variations in temperature can have some influence on the engineering characteristics of soil such as index properties, compaction and strength characteristics. Hogentogler [8] studied the compaction behaviour of several clay soils and reported that as the temperature increases, the optimum moisture content decreases and the maximum dry unit weight increases accordingly. Clay behaviour has been constantly related to its Atterberg limits. Atterberg limits could be used to appraise temperature vulnerability of a clayey soil. This indication was originally put forward by Tidfors and Sallfors [9]. Quite a number of studies have used Atterberg limit to jointly evaluate

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consistency and chemical compatibility of selected clay soils mostly used in hydraulic barrier construction [10].

Several researchers have evaluated the influence of temperature rise on the consolidation behaviour for different types of soils [11–14]. From their findings, it was found that as the soil temperature increases, the pre-consolidation pressure decreases. Abuel-Naga et al. [15] studied the effects of temperature on shear strength of clay, and results showed that temperature influence on shear strength of clay is strongly dependent on the volume change induced by heating. Hamidi et al. [16] found that heating could make the soil friction angle decrease, increase or stay unchanged. In as much as the inconsistency in soil behaviour can be hinged on its mineralogy and loading conditions, the reaction of clay mineralogy to elevated temperature could also have great influence on its engineering properties in service. Nicholson [17] reported that exposure of soil to elevated temperature leads reaction of clay minerals and evaporation of water. Temperature variation decreases the particle size in sandy soil, whereas in clayey soil, the particle size increases as a result of accumulation of clay fraction [7].

Cho et al. [18] studied temperature effects on hydraulic conductivity of compacted bentonite and concluded that the influence of temperature on the permeability of bentonite is a result of the viscosity and density of water. Similarly, Towhata *et al.* [19] and Villar and Lloret [20] investigated temperature effects on clayey soils and showed that the changes in viscosity of water with temperature have the most important mechanism in the change of soils properties. The strength of clay soil can be affected by its cation exchange capacity, CEC [21]. Goodman et al. [22] reported that beyond temperature of 100 °C, the CEC of buckshot clay soil decreased considerably.

Microscale investigations are significant for the reason that they complement and balance macroscale analyses and advance the understanding of unsaturated soil performance [22, 23]. Manahiloh and Meehan [23] utilised microstructural images achieved with X-ray computed tomography (CT) probing to measure the soil–water characteristic curve. Goodman et al. [22] used field emission scanning electron microscopy (FESEM) data to show minimal changes due to temperature effect on the fabric of unsaturated clay. Previous research work in the literature shows that researchers experimented the effect of temperature on soil properties at the peak of 120 °C [24], 150 °C [25] and 400 °C [26]. However, researches on microscale analysis of soil due to temperature variations are not in abundance and the effects of varying elevated temperature on the scanning electron microscopy of soil are not well understood. This study aims to experimentally evaluate the effect of elevated temperature on the geotechnical properties of clay soils (kaolinite). The study is a

follow-up phase of previously published work of Gadzama et al. [25]. The macroscale investigations which involve the laboratory testing are further enhanced qualitatively using microscale experiment (scanning electron microscopy) to explore microstructural behaviour of soils.

2 Materials and methods

2.1 Materials

2.1.1 Lateritic Soils

The disturbed soil samples used in the study were collected from two different locations. Sample 1 denoted as IBN was collected from a deposit at Ikot Inyang, Ibiono Ibom Local Government Area, while Sample 2 denoted as MKP was collected from a deposit opposite Akwa Ibom State University Teaching Hospital construction site at Ikot Ekong, Mkpato Enin Local Government Area, Akwa Ibom State, Nigeria. The samples were collected from an average depth of 1.0 m below existing ground surface to avoid organic material, placed in air tight bags and transported to the laboratory. The samples were thereafter air-dried completely, and the lumps were pulverised and sieved for different tests.

2.1.2 Sample preparation (heating temperature)

The soils (IBN and MKP) were heated in a furnace at various temperature sets of (25, 50, 100, 150 and 200 °C) for a period of about 4 h to undergo likely thermal past, after which the furnace was switched off. The crucible and its contents (soil) allowed for cooling while still in the furnace for about 24 h.

2.2 Methods

2.2.1 Index tests

Index tests were performed on the natural and heated soils according to the procedure outlined in BS 1377 [27] and BS 1924 [28], respectively.

2.2.2 Cation exchange capacity (CEC)

Replicate of three samples from the various heating temperature was analysed for CEC. The CEC test was performed in accordance with the procedures given by ISRIC [29]. The final result for each heating temperature was based on the average from three replicate tests. The CEC was calculated using the formula:

$$\text{CEC}(\text{Cmol/kg}) = \frac{(\text{Titre} - B) \times \text{NA}}{\text{Weight of soil}} \times 100 \quad (1)$$

where Titre = ml HCl required for titration sample, B = Blank = ml HCl required for titration blank extract, and NA = Normality of acid or molarity of acid.

2.2.3 Compaction

Compaction tests were performed on the natural and heated soils as outlined in BS 1377 [27] and BS 1924 [28] to determine the moisture–density relationship of the soil sample. British Standard Light (BSL) or Standard Proctor compaction test was used which involves compacting the soil in three layers with each receiving twenty 25 blows from a 2.5 kg rammer falling through a height of 300 mm. The blows were uniformly distributed over the surface of each layer during compaction.

2.2.4 California bearing ratio (CBR)

The test was carried out on the natural and heated soils as outlined in BS 1377 [27] and BS 1924 [28], respectively. The soil samples were mixed with their respective optimum moisture contents, and BSL compactive effort was applied for the compaction. The BSL involves the compaction of samples in three layers, and each layer receives 62 blows of 2.5 kg rammer. The compacted specimens were cured for duration of 6 days after which they were soaked for 48 h before testing as outlined in Nigerian General Specifications [30]. CBR was computed using;

$$\text{CBR} = \frac{\text{Measured load}}{\text{Standard load}} \times 100\% \quad (2)$$

2.2.5 Unconfined compression strength test (UCS)

The UCS test procedure of ASTM D-2166 [31] was used. The UCS specimens were compacted at their respective optimum moisture contents (OMC) and maximum dry density (MDD) into a cylindrical mould. The specimen was carefully extruded from mould and trimmed to the ratio of 2:1 which corresponds to 76 mm in height × 38 mm in diameter. The samples were then wrapped with poly-cellophane for 24 h to allow for uniform moisture distribution within the soil structure. The commencement of curing and stiffening process of samples at room temperature (25 ± 2 °C) began after the specimen was unwrapped and placed on the table in a relative humidity room. Specimens were then kept for the required 3, 7, 14 days before testing. Three representative specimens were used for each of the varying temperature, and UCS was evaluated using:

$$\text{UCS} = \frac{\text{Load at failure}}{\text{Cross sectional area at failure}} \quad (3)$$

2.2.6 Microanalysis

Scanning electron microscopy (SEM) test was conducted on the natural and heated samples to have understanding on the microstructural behaviour of the soil. Phenom ProX desktop SEM configured to detect particles size less than 100 µm was utilised in this investigation. Beam of high-energy electrons pre-set at 15 kV imaging was focused on the specimen such that it generates variety of signals which was transmitted or displayed as SEM image fixed at 536µm resolution and 500 × magnification.

2.2.7 Statistical testing

Basically, one-way ANOVA test and an F-statistic were done on the results because temperature was used as the only source of variation on the tested geotechnical properties. Also, this study used simple multiple regression and correlation statistics to establish the relationship between CBR and temperature, jointly with other geotechnical properties.

3 Results and discussion

3.1 Material characterisation

The summary of geotechnical investigation tests carried out on the natural lateritic soils of IBN and MKP is presented in Table 1. Oxide compositions are reported in Table 2. The high composition of silica, aluminium and iron oxides in the soils suggests that they are of kaolinitic origin. From physical observation, both soils are reddish brown and are classified as A-7-6(8) and A-7-5(10) according to AASHTO [32]. This indicates that the soils (IBN and MKP) are clayey, having liquid limit and plasticity index greater than 41 and 11, respectively. Based on USCS ASTM D-2487 [33], IBN and MKP soils are classified as SC and CL, respectively.

3.2 Temperature effect on Atterberg limits

Figure 1 demonstrates the liquid limit of IBN and MKP soils at varied heating temperatures. The liquid limit (LL) of both soils decreased slightly with increased heating temperature from 47.02% and 43.8% for natural soil (25 °C) to a minimum value of 42.37% and 35.75% (200 °C) for IBN and MKP soils, respectively. The reduction in liquid limit with increased heating temperature could be as a result

Table 1 Properties of the natural soils

Property	Quantity	
	IBN	MKP
Natural moisture content (%)	15.74	19.80
Percentage passing No 200 sieve (75 μ m)	42.40	58.10
Liquid limit (%)	49.30	43.20
Plastic limit (%)	20.50	21.10
Plasticity index	28.80	22.10
Specific gravity	2.58	2.60
AASHTO classification	A-7-6(8)	A-7-6(10)
USCS	SC	CL
Maximum dry density, Mg/m ³	1.825	1.798
Optimum moisture content (%)	13.1	12.35
California bearing ratio (24 h soaking) (%)	6	5
Unconfined compressive strength (KN/m ²)	135	138
CEC	41.5	47.2
Colour	Reddish brown	Reddish

Table 2 Oxide composition of IBN and MKP natural soils

Oxide	Concentration (%)	
	IBN	MKP
Lime (CaO)	0.42	0.3
Silica (SiO ₂)	40.35	36.35
Iron oxide (Fe ₂ O ₃)	25.67	27.41
Alumina (Al ₂ O ₃)	26.16	29.19
Manganese oxide (MnO)	0.019	0.028
Titanium dioxide (TiO ₂)	0.512	0.431
Sulphur oxide (SO ₃)	0.62	0.69
Zinc oxide (ZnO)	0.003	0.004
Loss on ignition (LOI)	5.6	4.8

Fig. 1 Variation in liquid limit of at varying temperature levels **Fig. 2** Variation in plastic limit at varying heated temperature levels **Fig. 3** Variation in plasticity index at varying heated temperature levels

of change in clay size fraction, surface charge and specific surface area of fabrics, dehydration and decomposition of soil particles, changes in mineralogy and variation in macro- and microstructure of the soils [34, 35]. Elevated temperature influences the LL of the soil such that it modifies the specific surface of the soil, its fabrics as well as interparticle contacts thereby giving rise to the reduction or disappearance of diffuse double layer [7]. This result is similar to the study of Tan et al. [36] who worked on variation in some engineering properties of clay with heat treatment and recorded a decrease in both liquid limit and plastic limit with increasing temperature.

The influence of temperature on the plastic limit of IBN and MKP soils is shown in Fig. 2. The trend shows a decrease in plastic limits of both soils with increased heating temperature. The decreasing trend in plastic limits due to elevated temperature could be attributed to the breakdown of its particles accompanied with the alteration in microstructure and mineralogical composition [7, 37].

Preheating temperature effect on the plasticity index of IBN and MKP soils is shown in Fig. 3. Results show that an overall decreased trend was corroborated for plasticity index of both soils. For MKP soil, the plasticity index decreased with increased preheat temperature from

27.30% for the natural soil (25 °C) to 26.85% at 150 °C after which it increased to 29.90% at 200 °C. Moreover, for IBN soil, the plasticity index decreased with higher temperature exposure from 32.06% for the natural soil (25 °C) to 22.73% at 200 °C. A possible explanation for this might be that the temperature of 200 °C causes de-hydroxylation of the clay minerals, followed by assembling of the particles and sintering [38]. The net effect is that the soil particles (kaolinitic) seem to become hydrophobic in nature. The hydrophobicity characteristics will affect plasticity and dynamic behaviour of the soil fabric such as particle–particle and particle–water phase interaction [36]. Interestingly, beyond 150 °C, the LL of IBN soil increased with a corresponding higher plasticity (Figs. 1 and 3). This could be due to the high tendency of extreme dehydration of the kaolinitic mineral above this temperature. Zihms et al. [7] reported higher LL values of 64% and 81% with corresponding increased plasticity at 500 °C and 750 °C, respectively.

In testing hypothesis, critical values are a point on the test distribution that is compared to the test statistic to conclude whether the null hypothesis will be rejected. If the absolute value of a test statistic F_{CAL} is greater than the critical value F_{CRIT} , statistical significance is declared and the null hypothesis is rejected. In such case, P value is usually less than 0.05, i.e. $F_{CAL} > F_{CRIT}$; $P \leq 0.05$. The one-way analysis of variance (ANOVA) test conducted on liquid limits of both soils is summarised in Table 3. Results showed that $F_{CAL} = 3.682$ and $F_{CRIT} = 5.317$ for IBN soil and $F_{CAL} = 4.095$ and $F_{CRIT} = 5.317$ for MKP soil. This implies

that $F_{CAL} < F_{CRIT}$, and contrary to expectations, temperature had no significant effect on tested soil property and was not statistically significant. The one-way analysis of variance (ANOVA) test conducted on plastic limits of both soils is summarised in Table 3. Results showed that $F_{CAL} = 8.106$ and $F_{CRIT} = 5.317$ for IBN soil and $F_{CAL} = 7.974$ and $F_{CRIT} = 5.317$ for MKP soil. This implies that $F_{CAL} > F_{CRIT}$, and therefore, temperature had significant effect on tested soil property and was statistically significant. The one-way analysis of variance (ANOVA) test conducted on plasticity index of both soils is summarised in Table 3. Results showed that $F_{CAL} = 5.529$ and $F_{CRIT} = 5.317$ for IBN soil and $F_{CAL} = 6.150$ and $F_{CRIT} = 5.317$ for MKP soil. This implies that $F_{CAL} > F_{CRIT}$, and therefore, temperature had significant effect on tested soil property and was statistically significant.

3.3 Effect of temperature on cation exchange capacity

The variation in cation exchange capacity (CEC) with temperature of selected fine grain soil is presented in Fig. 4. Although there was no appreciable variation between each set temperature especially from 25 to 150 °C, the trend is that of a general decrease with increasing temperature. It may be concluded that temperature does not greatly affect the CEC for this highly inorganic material. With soil that contains higher percentages of organic matter, it is more likely to see variation in CEC with temperature changes [39]. The justification for these results

Table 3 One-way analysis of variance for Atterberg limit and CEC at varying temperatures

Property	Soil	SOV	DF	F_{CAL}	P value	F_{CRIT}	Remark
Liquid limit	IBN	Temp	1 8	3.682	0.091	5.317	$F_{CAL} < F_{CRIT}$ NS
	MKP	Temp	1 8	4.095	0.077	5.317	$F_{CAL} < F_{CRIT}$ NS
Plastic limit	IBN	Temp	1 8	8.106	0.021	5.317	$F_{CAL} > F_{CRIT}$ SS
	MKP	Temp	1 8	7.974	0.022	5.317	$F_{CAL} > F_{CRIT}$ SS
Plasticity index	IBN	Temp	1 8	5.529	0.046	5.317	$F_{CAL} > F_{CRIT}$ SS
	MKP	Temp	1 8	6.150	0.038	5.317	$F_{CAL} > F_{CRIT}$ SS
CEC	IBN	Temp	1 8	4.732	0.061	5.317	$F_{CAL} < F_{CRIT}$ NS
	MKP	Temp	1 8	3.770	0.088	5.317	$F_{CAL} < F_{CRIT}$ NS

SOV source of variation, Temp temperature, DF degree of freedom, F_{CAL} F calculate (absolute value of test statistic), P value probability of failure, F_{CRIT} F critical (critical value of test statistic), SS statistically significant, NS not significant. Note that these abbreviations and their meaning are relevant to Tables 4, 5, 7 and 8

Fig. 4 Effect of elevated temperature on CEC of soils

Fig. 5 Variation in maximum dry density at varying temperature levels

stems from the idea that capacity of a clay particle to hold exchangeable cations depends on the size of the diffused double layer and the dipolar water that is attracted to that layer [40]. The assumption is that when the extreme temperatures are applied to the soil, this thickness is diminished because the heat removes the dipolar water from the diffused double layer and carries with it exchangeable cations. Thus, reduction in thickness of the diffused double layer also results to decreased CEC of soils.

The one-way analysis of variance (ANOVA) test conducted on cation exchange capacity of both soils is summarised in Table 3. Results showed that $F_{CAL} = 4.732$ and

$F_{CRIT} = 5.317$ for IBN soil and $F_{CAL} = 3.770$ and $F_{CRIT} = 5.317$ for MKP soil. This implies that $F_{CAL} < F_{CRIT}$, and therefore, temperature had no significant effect on tested soil property and was not statistically significant.

3.4 Compaction behaviour

Influence of temperature variation on the maximum dry density (MDD) of IBN and MKP soil is shown in Fig. 5. Results show that the MDD increased from their natural values of 1.825 and 1.798 Mg/m³ for IBN and MKP soils, respectively, to peak values of 1.857 and 1.870 Mg/m³ at 200 °C. The progressive increase in the maximum dry density of both IBN and MKP soils with increase in elevated temperature could be due to collapse of soil aggregate and the dispersed clay. The one-way analysis of variance (ANOVA) test conducted on maximum dry density of both soils is summarised in Table 4. Results showed that P values were less 0.05 such that preheating temperature before testing ($F_{CAL} = 7.708 > F_{CRIT} = 5.317$) for IBN soil and ($F_{CAL} = 7.709 > F_{CRIT} = 5.317$) for MKP soil had considerable effect on tested soil property by increasing its MDD values as earlier stated and is statistically significant (Table 3).

Effect of preheating temperature on optimum moisture content of IBN and MKP soils is revealed in Fig. 6. The OMC of IBN soil samples slightly increased to its peak value of 13.3% at 100 °C and afterwards decreased to 13.0% at 200 °C. The same trend was also observed for MKP soil but increased to maximum value of 12.55% at 100 °C and subsequently decreased to 12.45% at 200 °C. The initial increase in OMCs for both soils up to peak at 100 °C could be due to the fact that the clay content in the soil might still remain unaltered, and thus, the drying effect initiated up to 100 °C may have resulted in making the sample require additional moisture during compaction. It could also be said that the decrease in OMC beyond 100 °C might be associated with the improving characteristics of the soil where the diffuse double layer become reduced with resultant effect on the plasticity properties which also reduced. Elevated temperatures might initiate alterations in mineralogy

Table 4 One-way analysis of variance for compaction characteristics of soils at varying temperatures

Property	Soil	SOV	DF	F_{CAL}	P value	F_{CRIT}	Remark
MDD	IBN	Temp	1 8	7.708	0.024	5.317	$F_{CAL} > F_{CRIT}$ SS
	MKP	Temp	1 8	7.709	0.024	5.317	$F_{CAL} > F_{CRIT}$ SS
OMC	IBN	Temp	1 8	8.230	0.020	5.317	$F_{CAL} > F_{CRIT}$ SS
	MKP	Temp	1 8	8.353	0.020	5.317	$F_{CAL} > F_{CRIT}$ SS

Fig. 6 Variation in optimum moisture content at varying temperature levels

Fig. 7 Variation in California bearing ratio at varying temperature levels

that may be less possible to be sensed by visual inspection [41, 42]. Variations in the hydromechanical characteristics of the soils due to high temperatures may also cause changes in the optimum moisture contents as reported by a number of studies [18, 43–45]. One-way analysis of variance (ANOVA) test conducted on optimum moisture content of both soils is summarised in Table 4. Results show that $F_{CAL} = 8.230$ and $F_{CRIT} = 5.317$ for IBN soil and $F_{CAL} = 8.353$ and $F_{CRIT} = 5.317$ for MKP soil. This implies that $F_{CAL} > F_{CRIT}$, and therefore, pre-heating temperature had significant effect on tested soil property and was statistically significant ($P < 0.05$).

Table 5 One-way analysis of variance California bearing ratio

Property	Soil	SOV	DF	F_{CAL}	P value	F_{CRIT}	Remark
CBR	IBN	Temp	1	8.211	0.021	5.317	$F_{CAL} > F_{CRIT}$ SS
			8				
	MKP	Temp	1	8.873	0.017	5.317	$F_{CAL} > F_{CRIT}$ SS
			8				

3.5 Strength characteristics

3.5.1 California bearing ratio

The variation in CBR of IBN and MKP soil at varying pre-heating temperature is shown in Fig. 7. The temperature effect on the CBR values of the soil specimen indicates that an increase in temperature results to a corresponding increase in the CBR (soaked). The results for IBN and MKP soil increased from natural values (i.e. room temperature of 25 °C) of 6% and 5% to peak values of 20% and 13% at 150 °C, respectively. The increase could be attributed to changes in the structural fabric of the predominant clay minerals (kaolinite) of the soils. Furthermore, the sharp reduction in CBR that was noticed beyond 150 °C could be due to high temperature effect on the clay mineralogy and grain sizes which result in soil structure that exhibits high affinity for water [50]. The implication is that specimens heated up to elevated temperature of 150 °C are optimal at which the soils can be subjected to (in case of thermal remediation or stabilization) and still be suitable as sub-grade pavement material for road construction. Preheating temperature up to the threshold of 150 °C has shown to generally increase the CBR values, but this might not be unconnected with the hydromechanical behaviour of the soils as acknowledged by a number of studies [18–20, 25, 43–47].

Pavement subgrade is referred here because CBR value is one of the parameters used in assessing the suitability of soil material for subgrade, sub-base and/or base course of road pavement. Based on our results, specified 10% minimum CBR for subgrade as recommended in Nigerian General Specifications [30] was achieved for the soils (IBN and MKP). However, quite a number of researches on thermal remediation of soil concentrate more on the remediation outcome and eliminate the effects the technique will have on the engineering properties of the soil itself. The effects on soil properties (such as CBR) can be used as a benchmark for recommending or accepting the remediation technique (in the case of thermal) [48, 49].

The one-way analysis of variance (ANOVA) test conducted on California bearing ratio of both soils is summarised in Table 5. Results showed that $F_{CAL} = 8.211$ and $F_{CRIT} = 5.317$ for IBN soil and $F_{CAL} = 8.873$ and $F_{CRIT} = 5.317$ for MKP soil. This implies that $F_{CAL} > F_{CRIT}$, and therefore,

temperature had significant effect on tested soil property and was statistically significant.

3.5.2 Unconfined compressive strength test

The summit of the stress–strain plots is the peak stress corresponding to its strain at failure. The peak stress from the stress–strain plots (Figs. 8, 9 and 10) is the unconfined compressive strength, UCS. The summary of unconfined compressive strength of IBN and MKP samples with varying temperature and curing time is shown in Table 6. Highest values of UCS for both soils were achieved at 14 days curing. This might not be unconnected to the gradual loss of moulding water content such that the initial degree of saturation becomes even less at the time of testing.

Generally, UCS decreased with increased preheating temperature. This might be related to the clay mineralogy, microstructural alterations and change in physicochemical behaviour of clay to water in relation to diffuse double layer with elevated temperature. It could be that preheating temperature had destroyed the clay particle structure and mineralogy that was previously formed in the initial process of deposition. Hitherto, the effect was observed when coarser grain sizes were mainly formed due to reduction in clay content, therefore initiating a reduction in plasticity properties of both soils.

The two-way analysis of variance (ANOVA) test conducted on UCS of both soils is summarised in Table 7. Results showed that $F_{CAL} > F_{CRIT}$, and therefore, temperature and curing time had significant effect on tested

Fig. 8 Stress–strain plot of soil specimens cured for 3 days

Fig. 9 Stress–strain plot of soil specimens cured for 7 days

Fig. 10 Stress–strain plot of soil specimens cured for 14 days

Table 6 Summary of unconfined compression strength tests

Soil sample	Temperature (°C)	Unconfined compressive strength (kN/m ²)		
		3 days	7 days	14 days
IBN soil	25	114	135	158
	50	105	131	150
	100	107	124	160
	150	99	119	145
	200	91	115	140
MKP soil	25	130	140	164
	50	132	134	152
	100	124	120	155
	150	105	119	131
	200	110	118	121

soil property. Similarly, the one-way analysis of variance (ANOVA) test conducted on UCS of both soils is summarised in Table 8. Results showed that $F_{CAL} < F_{CRIT}$, this implies that temperature alone had no effect on tested soil property.

Table 7 Two-way analysis of variance of unconfined compressive strength

Property	Soil	SOV	DF	F_{CAL}	P value	F_{CRIT}	Remark
UCS	IBN	Temp	4	17.773	4.81E–04	3.838	$F_{CAL} > F_{CRIT}$ SS
		curing time	2	258.726	5.37E–08	4.459	$F_{CAL} > F_{CRIT}$ SS
	MKP	Temp	4	10.160	3.18E–03	3.838	$F_{CAL} > F_{CRIT}$ SS
		curing time	2	17.283	1.25E–03	4.459	$F_{CAL} > F_{CRIT}$ SS

3.6 Microanalysis of specimens

A number of studies have reported the use of microstructural analysis in soil testing [50–52]. The morphological observation obtained with the aid of scanning electron microscope for the natural soil (25 °C) and heat-treated soils of IBN and MKP, respectively, is presented in Figs. 11, 12 and 13. In the natural state (25 °C), IBN shows a porous-like structure, whereas MKP does not show the same but rather show a partially smooth to rough morphology (Fig. 11). Furthermore, when preheated to 150 °C (Fig. 12), IBN soil shows a distinctive appearance which is likely made up of fragmented surface structure. MKP revealed a porous-like structure with some conspicuous pore spaces. The SEM micrographs at 200 °C (Fig. 13) show smooth to rough morphological properties for the both soils. The results show that high preheating temperatures can have critical effects on the microstructural orientation and distinctiveness of the clay. Generally, the morphological change with variation in temperature might be due to the deformation or breakdown of soil fabrics, change in basic mineral composition as well as variations in the physicochemical and chemical processes that took place during heating.

Table 8 One-way analysis of variance of unconfined compressive strength

Property	Soil	SOV	DF	F_{CAL}	P value	F_{CRIT}	Remark
UCS _{3days}	IBN	Temp	1 8	0.003	0.957	5.318	$F_{CAL} < F_{CRIT}$ NS
	MKP	Temp	1 8	0.219	0.652	5.318	$F_{CAL} < F_{CRIT}$ NS
UCS _{7days}	IBN	Temp	1 8	0.377	0.556	5.318	$F_{CAL} < F_{CRIT}$ NS
	MKP	Temp	1 8	0.430	0.530	5.318	$F_{CAL} < F_{CRIT}$ NS
UCS _{14days}	IBN	Temp	1 8	2.001	0.195	5.318	$F_{CAL} < F_{CRIT}$ NS
	MKP	Temp	1 8	1.440	0.264	5.318	$F_{CAL} < F_{CRIT}$ NS

Fig. 11 Morphology of natural soil, i.e. at 25 °C, for **a** IBN soil and **b** MKP soil, both soils taken at 536 μ m resolution and 500 $\times$ magnification

Porous structure of interconnected grain of IBN at 25°C (natural form)

Fig. 12 Morphology of specimen heated at 150 °C for **a** IBN soil and **b** MKP soil, both soils taken at 536 μm resolution and 500 $\times$ magnification

Fig. 13 Morphology of specimen heated at 200 °C for **a** IBN soil and **b** MKP soil, both soils taken at 536 μm resolution and 500 $\times$ magnification

3.7 Statistical analysis

3.7.1 Comparison between measured and predicted California bearing ratio (CBR) values

Several geotechnical researches have used simple and multiple regression analysis to correlate and develop workable models [25, 53–57]. Gadzama et al. [25] after establishing the effect of temperature on expansive soils used it along with other associated parameters to correlate and proposed useful model for CBR. The use of temperature as part of independent parameters to correlate the stiffness property (CBR) of soils has not been given much attention. Thus, the statistical analysis in this study is a follow-up to Gadzama et al. [25] who used highly expansive black clay soils which are completely different in terms of origin, formation and mineralogy composition from soils considered in this research. Simple linear regression model was formulated from laboratory results of IBN and MKP soils using Minitab R15. In the model, CBR value is considered as dependent variable, while soil parameters such as maximum dry density (MDD), optimum moisture content (OMC), temperature (TEMP) and plasticity index (PI) are

considered as independent variables as shown in Eqs. (4) and (5) for IBN and MKP soils, respectively.

$$CBR_{IBN} = 68.5 - 267MDD + 20.6OMC + 0.242TEMP + 5.42PI \quad (4)$$

$$CBR_{MKP} = 224 - 179MDD + 9.62OMC + 0.104TEMP - 0.562PI \quad (5)$$

For IBN soil, the regression model portrays a strong connection existing between the dependent variable (CBR) and the independent variables (MDD, OMC, TEMP and PI). From the regression model, a plot of predicted CBR and measured CBR values indicates a strong relationship with a high correlation coefficient $R^2 = 99\%$ and $R^2 = 100\%$ for IBN and MKP soil, respectively (see Fig. 14). Also, the high R^2 values of IBN and MKP soils imply that the experimental results are highly correlated with the predicted results. Hence, this is also an indication that the model is fit and adequate. The percentage errors between CBR_{LAB} and CBR_{PRED} results were very minimal and ranged from 0.029 to 2.788% and from 0.869 to 1.111% for IBN and MKP soils, respectively (Table 9).

3.7.2 Correlation analysis for IBN and MKP soils

The level of relationships between California bearing ratio (dependent variable) and each of the independent variable (parameter) was revealed by the outcome of correlation analysis. The CBR of IBN soil after which correlated with related constraints (MDD, OMC, TEMP, PI and CEC) shows varying measure of relationships. Negative correlations were observed between CBR and PI (-0.373 ; $P = 0.537 > 0.05$); CBR and CEC (-0.730 ; $P = 0.162 > 0.05$). Similarly, positive correlations were recorded between CBR and MDD (0.733 ; $P = 0.159 > 0.05$); CBR and OMC (0.057 ; $P = 0.928 > 0.05$); CBR and TEMP (0.665 ; $P = 0.221 > 0.05$) (Tables 10, 11). Basically, all parameters that are related to CBR (MDD, OMC, TEMP, PI, and CEC) have very low-level correlation with the CBR values. This result suggests that values from only one of any such parameters would not

Fig. 14 Plot between predicted CBR and measured CBR of IBN and MKP soils

Table 9 Measured and predicted CBR values of IBN and MKP soils

Soil type	Temperature	CBR _{LAB}	CBR _{PRED}	Absolute error	Percentage error
IBN	25	6	6.00	0.0003	0.029
	50	10	9.95	0.0050	0.499
	100	16	15.85	0.0096	0.960
	150	20	19.74	0.0129	1.289
	200	13	12.64	0.0279	2.788
MKP	25	5	5.05	0.0103	1.026
	50	7	7.06	0.0092	0.916
	100	10.2	10.29	0.0087	0.869
	150	13	13.11	0.0087	0.872
	200	12.4	12.54	0.0111	1.111

Table 10 Correlation matrix for IBN soil

	CBR	MDD	OMC	TEMP	PI	CEC
CBR	1					
MDD	0.733	1				
OMC	0.057	−0.464	1			
TEMP	0.665	0.981	−0.535	1		
PI	−0.373	−0.864	0.565	−0.927	1	
CEC	−0.730	−0.962	0.457	−0.988	0.897	1

Table 11 *P* values for IBN soil

	CBR	MDD	OMC	TEMP	PI	CEC
CBR	1					
MDD	0.159	1				
OMC	0.928	0.432	1			
TEMP	0.221	0.003	0.353	1		
PI	0.537	0.059	0.321	0.023	1	
CEC	0.162	0.009	0.439	0.002	0.039	1

Table 12 Correlation matrix for MKP soil

	CBR	MDD	OMC	TEMP	PI	CEC
CBR	1					
MDD	0.949	1				
OMC	0.593	0.431	1			
TEMP	0.938	0.997	0.388	1		
PI	−0.822	−0.635	−0.599	−0.601	1	
CEC	−0.971	−0.996	−0.469	−0.993	0.684	1

Table 13 *P* values for MKP soil

	CBR	MDD	OMC	TEMP	PI	CEC
CBR	1					
MDD	0.014	1				
OMC	0.292	0.431	1			
TEMP	0.018	0.000	0.518	1		
PI	0.088	0.249	0.285	0.283	1	
CEC	0.006	0.000	0.426	0.001	0.203	1

be sufficient to adequately predict the CBR values for subgrades road pavement using IBN soil. Hence, all variables were considered in generating a simple multiple linear regression model for IBN soil.

MKP soil indicated very high positive correlation between CBR and MDD (0.949 ; $P = 0.014 < 0.05$); TEMP (0.938 ; $P = 0.018 < 0.05$). Also, low positive correlation was observed between CBR and OMC (0.593 ; $P = 0.292 > 0.05$). In the pair of CBR and PI ($−0.822$; $P = 0.088 > 0.05$); CEC ($−0.971$; $P = 0.006 < 0.05$), high negative correlations were recorded (Tables 11, 12 and 13). Exclusive of MDD

and TEMP, all other parameters that are related to CBR (OMC, PI and CEC) have very low-level correlation with the CBR values of MKP soil. This result suggests that numerical parameters from either MDD or TEMP will be adequate to predict the CBR values for subgrades road pavement using MKP soil. However, due to variation in test condition and other unseen factors which can only be verified qualitatively, it will be necessary to take into consideration several determining factors in predicting the CBR values of preheated soils.

4 Comparison with previous studies

The liquid limit and plasticity index of IBN and MKP soils (kaolinitic clay mineral) showed a decreasing trend with increase in temperature. In contrast to Gadzama et al. [25] who used black clay (montmorillonite), they reported consistent trend for liquid limit decreasing with increase in temperature on one hand and on the other hand concluded that no actual relationship exists between temperature and plasticity index. However, both studies used tropical soils but of different clay mineralogy and composition. Fookes [58] maintained that all tropical residual soils are in certain way influenced by temperature. Also, the plastic limit and plasticity index of the current study are consistent with those of Zhang et al. [59], who reported that the influence of drying on Atterberg limits of weathered soil is more complex due to interparticle bonding. In accordance with the present results, previous studies have demonstrated the increase in MDD with increase in temperature [25, 26, 60]. However, the OMCs trend of the current study (Fig. 6) does not support previous researches [25, 26, 60]. Gadzama et al. [25] reported little or no effect of temperature on optimum moisture content (OMC) as their trends were observed to be inconsistent. Similarly, Hanuma and Prasad [26] and Estabragh et al. [60] reported the decrease in OMC with increase in temperature. It is encouraging to compare Fig. 7 with that found by Gadzama et al. [25] who found that CBR stiffness increased from 25 °C (the room temperature) to 100 °C and afterwards decreased. Similarly, Hanuma and Prasad [26] reported the continuous increase in CBR of heat-treated soils (black expansive clay and reddish clay soil) from the temperature of 100 °C up to 400 °C. The authors believed that the corroboration of CBR with hydromechanical behaviour of the soils as earlier stated (refer to 3.5.1) might not be unrelated to the effect of particle size structure and composition, absence or presence of a granular bearing soil structure, secondary fabric of silt–clay clusters, the mechanical and thermal alteration to physicochemical properties and moisture history of the soil phase [61, 62]. Unexpectedly, the UCS observed in this study decreases with increase in temperature but increases with curing age interval of 3, 7 and 14 days. These results seem to be consistent with those of Hanuma and Prasad [26], who considered UCS testing at 3, 7, 14 and 21 days curing in the temperature range of 100–400 °C. The statistical analysis used in this study upholds the research of Gadzama et al. [25] who showed that temperature has positive effect on CBR values of soil for engineering use.

5 Conclusions

The present study was designed to investigate the effect of temperature variation on the geotechnical properties of selected lateritic soils. The results of this investigation show that elevated temperature in the form of preheated thermal exposure results in changes in the various soil properties and the following specific conclusions are drawn:

- This research has found that the Atterberg limit decreased with increase temperature, while the maximum dry density (MDD) increased with increase in temperature. No significant change for optimum moisture content (OMC) was obvious with increase in temperature.
- The CEC of both soils decreased significantly with temperatures above 150 °C as peak CBR for both soils was obtained at 150 °C.
- The unconfined compression strength of both soils decreased with temperature and expectedly increased with curing time.
- The SEM analysis reveals that there is evident change in the morphology as a result of temperature variations.
- The evidence from this study suggests that the influence of temperature appears to show some slight and major variations between the two samples. This is particularly due to the varying particle size structure, mineralogical layout and silt–clay assemblages of these two soil constituents.
- This research also shows that some results are in contrast to parallel tests (reddish brown clay (kaolinite) compared to tropical black clay (montmorillonite), and this underscores the complexity and variation in soils in line with their engineering behaviour.
- The statistical analysis (multiple regression and correlation statistics) has shown that temperature (TEMP) besides PI, OMC and MDD variables are reliable predictors of engineering properties of soil. Taken together, these results suggest that 150 °C is the optimal temperature recommended for enhancing the soils behaviour.
- Further experimental investigations on microstructural behaviour apart from SEM would be needed to estimate the veracity on effect of temperature on silt-to-clay size fraction, porosity and pore size distribution, change in mineralogical composition, diffuse double layer phenomenon and chemical constituent. Although the study has successfully demonstrated that temperature has significant effect on the engineering properties and morphological microscopy of

the soils, it is recommended that widespread studies be carried out on soils of dissimilar origin and properties.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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