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Assessment of Index Properties and Compaction Characteristics of Heat-Treated Laterite for Rural Road Pavement Construction

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Abstract-

This study assessed the impact of heat treatment on the index properties and compaction characteristics of lateritic soils for rural road pavement construction. Four lateritic soils sourced from MGA, MGC, MGB, and Yogbo Road were subjected to heat treatments at varying temperatures of 50°C, 100°C, 150°C, and 200°C. The Atterberg limits, specific gravity, maximum dry density (MDD), and optimum moisture content (OMC) of the samples were analyzed. The results indicated a significant reduction in plasticity (liquid limit, plastic limit, and plasticity index) as heat treatment temperatures increased, with the most notable reductions observed up to 100°C. Beyond 150°C, the soils exhibited minimal further improvement, and at 200°C, some soils, particularly soils from MGA and Yogbo Road, became non-plastic. MDD values improved up to 100°C, with a peak of 2.28 g/cm³ for Yogbo Road soil, after which MDD values plateaued or slightly declined. Specific gravity values varied, with a significant increase at 200°C for most soils. The findings suggest that controlled heat treatment can enhance the suitability of lateritic soils for rural road pavement construction by improving compaction and reducing moisture sensitivity. Further research on mineralogical transformations for the heat-treated temperatures used in the research and those at higher temperatures is recommended to optimize the heat treatment process for practical applications.

Keywords: Heat treatment, Index properties, Compaction characteristics, Rural Road pavement construction.

1. INTRODUCTION

The concept of 'laterite' was first documented in scientific literature by Buchanan in 1807, originating from his observations of soil characteristics in Malabar's mountainous regions in India [1-11]. Lateritic soils form as residual products of intense chemical weathering and leaching processes in tropical and subtropical climates, where processes of laterisation transform rock material into iron- and alumina-rich soils [2,4-5,12-18]. These soils are globally distributed, exhibiting unique physical, chemical, and geological properties due to factors like climatic conditions, parent rock composition, and weathering depth [2,12-13,17].

Lateritic soils form under warm, humid conditions, where high rainfall and temperatures promote the laterisation process, leading to significant concentrations of iron-alumina sesquioxides [2, 19-21]. This process includes stages of mineral decomposition, leaching of silica and lime, and the eventual precipitation of iron and alumina oxides, with rainfall intensity being a critical factor [22]. With rising demand for natural resources such as sand and aggregate in construction, lateritic soils present a sustainable alternative due to their abundance and resilience, especially for rural road construction. By leveraging their characteristic fine particles and mineral content, lateritic soils can mitigate some sustainability concerns related to raw material scarcity and environmental degradation.

Found predominantly in tropical climates, laterite is distinguishable by its red to purplish-brown hues and compacted structure, containing cementitious compounds that contribute to its strength and durability [15,17,23-25]. The distinct layered structure of lateritic soil is comprised of five zones: topsoil, laterite, mottled, pallid, and bedrock [26-28]. Soil texture and cohesiveness vary based on the particle size distribution, with clay-based laterites typically more cohesive compared to sand-based types [9]. The soil's geotechnical properties—including a wide range of liquid and plastic limits, shear strength, and water absorption—vary based on both depth and climate conditions [4,29]. Laterite's high alumina and iron oxide content constitute the majority of its chemical composition, with mineral elements such as silicon, zirconium, and titanium helping classify the soil by its silica-alumina ratio [30-31]. Such high flux and immobile elements contribute to the soil's resilience in construction applications, particularly as it can maintain structural integrity under varied environmental [32-33]. Further, kaolinite, quartz, goethite, and calcite are commonly found minerals, each influencing the soil's mechanical and thermal response to environmental conditions [15 ,21, 34].

Studies have shown that lateritic soil's mineral composition and geotechnical properties undergo substantial changes at elevated temperatures. Studies have observed that heating can reduce plasticity, enhance load-bearing capacity, and even impact mineralogical composition, often beneficial for use in road pavement construction where durability and resilience to environmental factors are [35–37] Using stabilizers like lime and cement has effectively enhanced lateritic soil performance, especially under cycles of wetting, drying, and temperature fluctuations. This makes it a valuable resource for road base layers in rural infrastructure projects where resources may be limited [23].
As a prevalent soil type in tropical regions, lateritic soil is widely applied in embankments, compacted liners, and road pavements due to its resilience and cost-effectiveness [5, 38-39]. In rural road construction, heat-treated laterite stabilized with suitable binders enhances durability and sustainability, addressing challenges associated with conventional materials.

Particularly in rural road construction, using heat-treated laterite stabilised with suitable binders can enhance both durability and sustainability, contributing to infrastructure longevity and reduced maintenance costs, all while addressing the sustainability challenges associated with conventional construction materials.

Heat treatment, an underexplored method for improving lateritic soils, involves subjecting soil to elevated temperatures to alter its physical and chemical properties. Heating leads to clay mineral dehydration, reducing plasticity and improving compaction characteristics, thereby enhancing stability and load-bearing capacity [40]. Studies indicate that heating soils to moderate temperatures (50°C to 200°C) significantly reduces plasticity and increases density, making them suitable for road pavements. For instance, Owoyemi and Afolagboye [37] demonstrated that cyclic heating and cooling could modify the index and engineering properties of lateritic soils from Ilorin, Nigeria. The effect of temperature on the engineering behaviour of soil has become a key focus within geotechnical and geoenvironmental engineering. In recent times, numerous studies have examined the impacts of elevated temperatures on soil properties [41-42]. However, as observed by Geng and Sun [43], there remains a lack of sufficient understanding regarding the thermo-physical properties of clay exposed to high temperatures (above 200 °C) and the interrelationship between thermo-physical and chemical parameters.

The primary objective of this research is to assess the effect of heat treatment on the index properties and compaction characteristics of laterite soils from four sample locations within Makurdi Local Government Area of Benue State of Nigeria. By subjecting these soils to varying heat treatment temperatures (50°C, 100°C, 150°C, and 200°C), the study evaluates how heating influences their liquid limit (LL), plastic limit (PL), plasticity index (PI), specific gravity (Gs), maximum dry density (MDD), and optimum moisture content (OMC). These properties are crucial in determining the suitability of soil for road construction, as they affect compaction, stability, and resistance to deformation [44].

This study is built on existing research by exploring the potential of heat treatment to enhance the engineering performance of lateritic soils, particularly for rural road construction in this region. It focuses on the effect of heat on the index properties and compaction characteristics of lateritic soils in the Makurdi Local Government Area of Benue State. The findings aim to address a research gap by providing insights into how heat treatment influences these properties, as studies in the area have been limited in this specific region. This research seeks to specifically assess index properties and compaction characteristics of these often considered problematic soils in this region, by examining the effects of elevated temperatures on their performance.

The outcomes may also establish heat treatment as a viable method for soil improvement, contributing to more effective infrastructure development in tropical regions.

2.0 METHODS

2.1 Materials

The materials used for this study were four lateritic soils from different locations and clean water. The soil samples were collected during the early part of the rainy season in May from four locations within Makurdi, Benue State, Nigeria. Three of the samples were taken from Mbaagi Community in Ugondo District, and the fourth was collected along Yogbo Road, North Bank.

- **Sample MGA:** Located along Gideon Orkar Road, before Eunice Spring of Life Hospital and Foundation (7°38'44.32"N, 8°35'47.81"E).
- **Sample MGB:** Collected before Orkar Christian Academy (7°38'09.14"N, 8°35'08.51"E).
- **Sample MGC:** Collected from a borrow pit opposite Community Secondary School (7°38'11.49"N, 8°34'42.71"E).
- **Sample YR:** Collected after NASME Barracks around Uga, along North Bank–Yogbo Road (7°46'54.05"N, 8°31'16.72"E).

Disturbed method of soil collection was employed, with a digger and shovel used to excavate to a depth of approximately 1.5 metres. This depth represents the B-horizon, typically characterised by the accumulation of materials leached from the overlying A-horizon.

2.2 Methods2.2.1 Samples pretreatment

Collected samples were air-dried before laboratory testing.

The tests were conducted in two phases: before and after heat treatment. Key parameters measured include:

a) Index Properties:
- Atterberg Limits (Liquid Limit, Plastic Limit, and Plasticity Index): To assess the soil's plasticity and workability.
- Specific Gravity: To measure the density of the soil particles.
- Sieve Analysis: To determine particle size distribution. Just for the untreated samples

b) Compaction Characteristics:
- Maximum Dry Density (MDD): To assess the highest dry density achieved by compacting the soil at varying moisture contents.
- Optimum Moisture Content (OMC):

To determine the moisture level at which the soil achieves maximum compaction

2.2.2 Samples Heat Treatment (Calcination)

Soil samples were subjected to calcination at four different temperatures: 50°C, 100°C, 150°C, and 200°C. The samples were heated in a temperature controlled locally fabricated reactor with a sensitive thermometer installed for correct reading of temperature rise. Samples were allowed to cool before testing. Fig.1 shows the heating process set up.

Fig. 1. Sample Heat Treatment Set up

2.2.3 Particle Size Distribution

BS 1377:1990 Part 2[45] was adopted, as the sedimentation method for grading is seldom used in road construction [46], and thus the dry sieve analysis procedure was employed. Representative samples were obtained and oven-dried at 105°C–110°C for 24 hours to eliminate moisture.

The procedure commenced with the breaking of lumps in the dry soil using a mallet, ensuring the particles were not crushed. The soil was then thoroughly mixed and subdivided to obtain the test sample. The mass of the test sample was measured and recorded as M_1. Each sample was washed in small portions using either a 1.18 mm or 2.36 mm sieve, nested above a 0.075 mm sieve. The washed material was dried in an oven to a constant weight, and the sample was placed on the top sieve, ranging from 22.22 mm down to 0.075 mm. It was then shaken for 10–15 minutes to allow particles to pass through. The cumulative weight retained on each sieve was recorded as M_2, and the percentages of material retained and passing were calculated. Finally, the data was plotted on a semi-logarithmic graph, with sieve sizes on the x-axis and cumulative percentage passing on the y-axis.

2.2.4 Atterberg Limits

The Atterberg limits test involves determining the liquid limit, plastic limit, and plasticity index of both natural and heat-treated soils. These tests were carried out in accordance with BS 1377 Part 2, Test 3[45].

2.2.5 Compaction Test

Compaction tests were conducted on both the natural soils and soils subjected to heat treatment of 50°C, 100°C, 150°C and 200°C using British Standard Heavy (BSH) compaction energy (4.5kg rammer) – 5 layers, 27 blows per layer, following BS 1377-4[45] and the Nigerian General Specifications [47].

3.0 RESULTS AND DISCUSSION

3.1 Soils Identification

The findings from the identification test on the natural soils are presented in Table 1.

Table 3.1: Characteristics of Untreated Natural Soils

Characteristic	Value (Quantity or Quality)			
	Soil Designation			
	MGA	MGC	MGB	YR
Percentage passing BS No 200 sieve	31	45	14	30
Liquid Limit (%)	66.6	38.2	Non plastic	34.1
Plastic Limit (%)	36.4	16.7	ditto	17.8
Plasticity Index (%)	30.2	21.5	Non plastic	16.3
Specific Gravity	2.52	2.56	2.65	2.65
AASHTO Classification	A-6	A-6	A-1-a	A-2-6
USCS	CH	CL	SP	SC
NBRRI Classification	High plasticity clay	Silty Clayey Gravel/Sand	well-graded sand	Clayey material
Maximum Dry Density (g/cm3) (BS Heavy Compaction)	2.11	1.90	2.18	2.21
Optimum Moisture Content (%)	11.5	12.6	7.5	8.0
Colour	Brown	Reddish	Dark reddish	Dark yellowish

3.2 Particle Size Distribution

The particle size analysis using Dry Method of testing for the untreated soils is shown in Fig. 2.

The particle size distribution (PSD) analysis of the four natural lateritic soils (MGA, MGC, MGB, YR) reveals distinct gradation patterns:

- **MGA** has a higher percentage of coarse particles, making it suitable for base layers with good load-bearing capacity, though careful compaction is needed to manage fines.
- **MGC** is finer with a higher percentage of small particles, which may compact

well but could be prone to plastic deformation, requiring stabilization.

- **MGB** is granular with fewer fines, making it ideal for subbase layers due to its drainage properties and low plasticity.
- **YR** has a balanced gradation, suitable for versatile use in both base and subbase layers, but may also need stabilization to control plasticity in moist conditions.

The Federal Ministry of Works and Housing Specification [47] states that for a soil sample to qualify as both subgrade/fill and base material, the percentage passing the No. 200 sieve (75 μm) must be less than 35%. If the percentage passing the No. 200 sieve for a lateritic base course exceeds 35%, the material is automatically disqualified without further testing. Therefore, in their natural state, only sample MGC does not meet the criteria for use as subgrade/fill and base material without heat treatment.

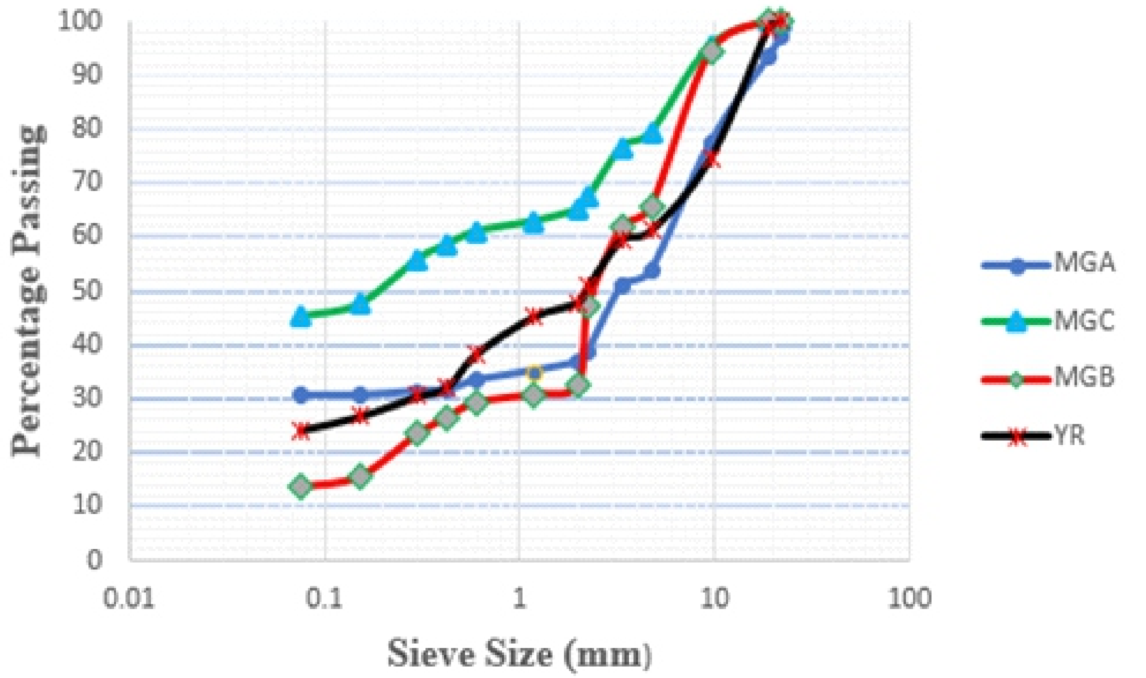

Fig. 2. Particle Size Distribution curves of Untreated Soils

3.3 Effect of Heat Treatment on Atterberg Limits and Specific Gravity

The test results for Atterberg Limits of the three different cohesive laterite soils subjected to varying temperatures demonstrated the effect of heat treatment on the index properties of these soils.

3.3.1 Liquid Limit (LL)

The liquid limit (LL) test results indicated a significant variation in the behaviour of cohesive laterite soils from the three different sample locations when subjected to increasing heat treatment temperatures. At room temperature, the ***MGA*** sample showed the highest LL (66.6%), while **MGC** (38.2%), and **Yogbo Road** (34.1%) has lower values. The heat-treated samples revealed a general trend of decreasing LL values with increasing temperatures, particularly after 100°C, with the values reaching zero at 200°C. This suggests that thermal treatment reduces the soils' water retention capacity. The values of LL accompanying variation in temperature are graphically shown in Fig.3.

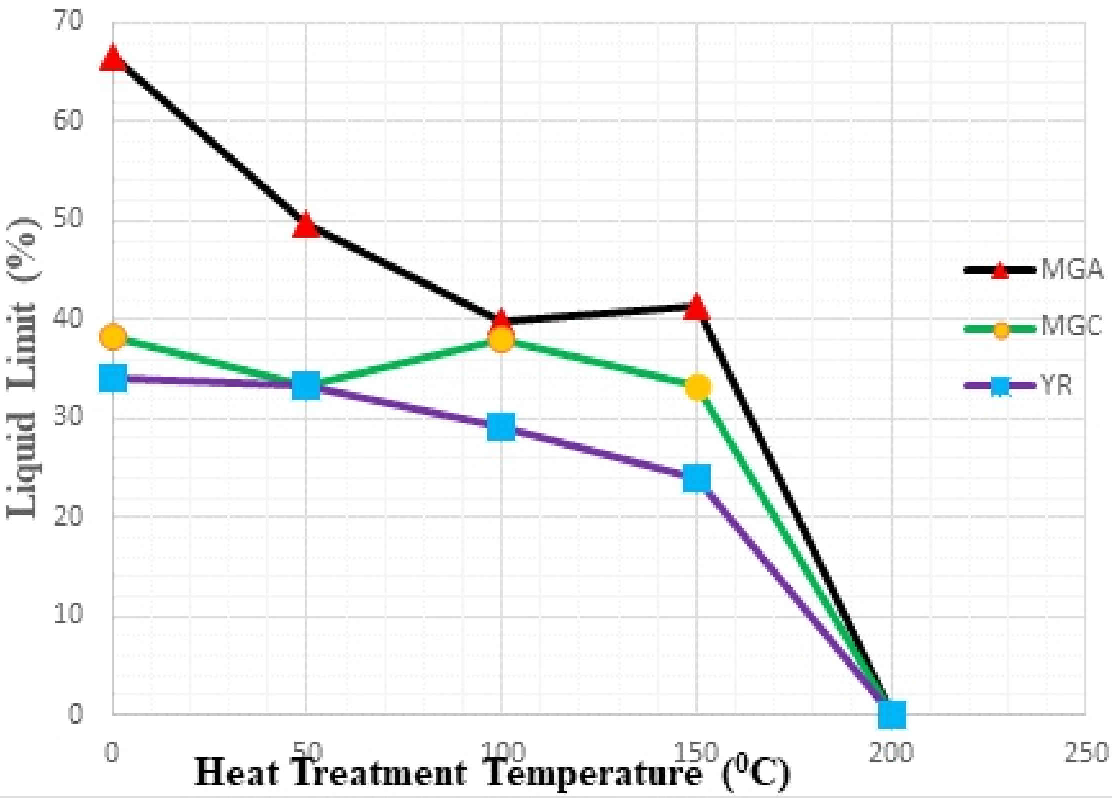

Fig.3. Variation of Liquid Limit with Heat Treatment Temperature

The reduction in liquid limit with increasing temperature can be attributed to the thermal alteration of the soil's clay minerals, which are primarily responsible for water retention. This agrees with Sunil and Deepa [48], who observed that increasing drying temperature causes soil particles to aggregate and cluster. This particle agglomeration decreases the soil's surface area available for water interaction, leading to reduced water absorption. Consequently, the soil exhibits a lower liquid limit and reduced plasticity. The sharp decrease in liquid limit at 200°C could be due to complete dehydration and loss of the soil's plasticity properties.

3.3. 2. Plastic Limit (PL)

Fig.4 demonstrates the plastic limit (PL) for the three soils reflecting a decreasing trend with increasing heat treatment. For ***MGA***, the initial PL of 36.4% drops slightly to 33.0% at 50°C and remains relatively stable around 29.2% to 35.5% up to 150°C before dropping to 0% at 200°C. ***MGC*** and **Yogbo Road** display a similar pattern, with their values decreasing more steadily. The findings indicated a clear trend of decreasing plasticity as heat treatment increases. This implies that, even within the CL classification, the soil becomes progressively less plastic with exposure to temperature up to 200 °C. This reduction in plasticity may be due to the onset of clay mineral dehydroxylation at this temperature, which lowers the soil's water adsorption capacity—a primary factor affecting plasticity [49]. Additionally, elevated temperatures may encourage particle aggregation and sintering, further diminishing the soil's overall plasticity [50]. The complete reduction of the plastic limit at 200°C indicates a loss of the material's ability to undergo plastic deformation, a phenomenon linked to the loss of interparticle bonding caused by the breakdown of clay minerals.

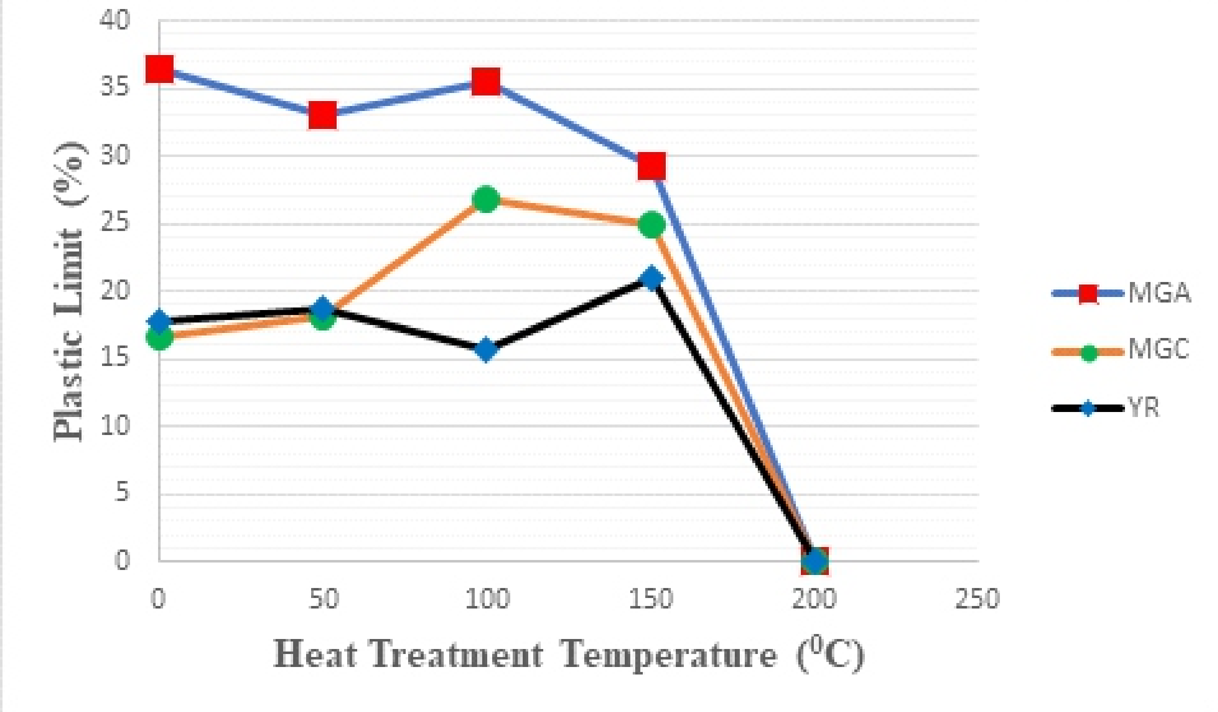

Fig. 4. Variation of Plastic Limit with Heat Treatment Temperature

3.3.3 Plasticity Index

The plasticity index (PI) measures the difference between the liquid and plastic limits, representing the range of moisture content over which the soil remains plastic. For ***MGA***, the initial PI is 30.2% at room temperature, which decreases significantly to 4.4% at 100°C and 0% at 200°C. Similarly, the PI for ***MGC*** starts at 21.5% and drops to 0% at 200°C, following a consistent decline. Yogbo Road follows a similar trend. This trend is demonstrated by Fig.5.

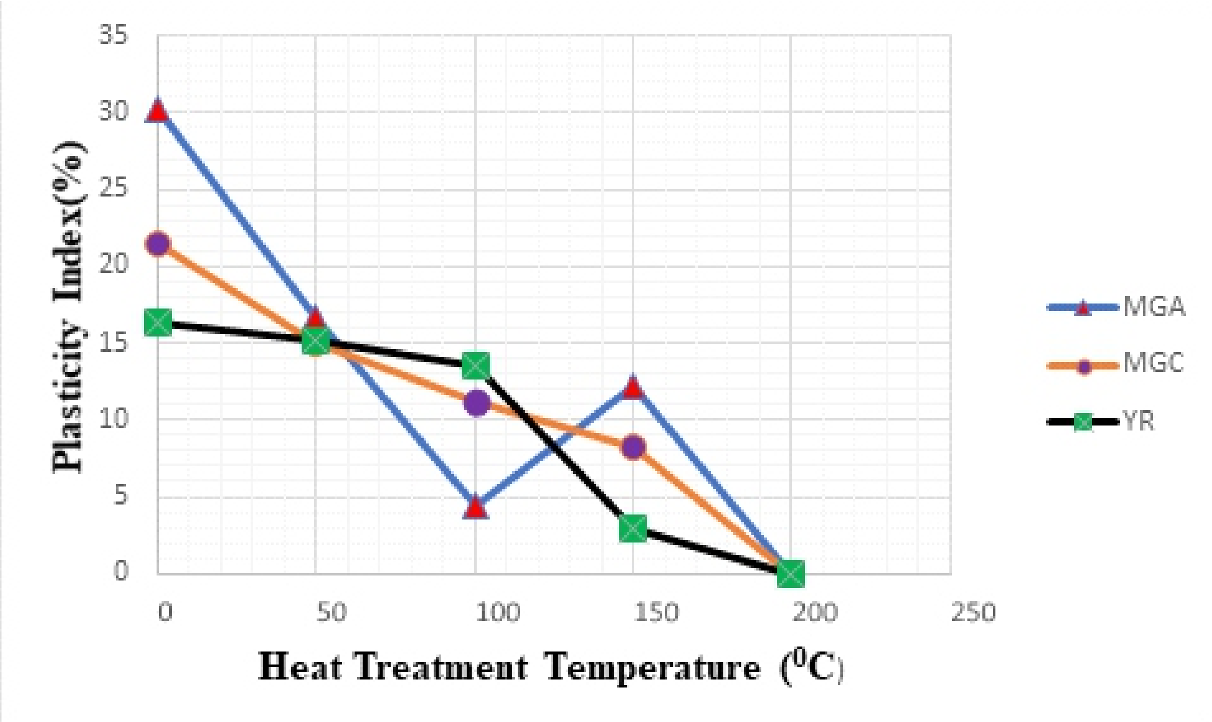

Fig. 5. Variation of Plasticity Index with Heat Treatment Temperature

The reduction in the plasticity index is consistent with the general understanding of heat-treated soils, one possible explanation for this decrease is the dehydroxylation of clay minerals at elevated temperatures, which promotes particle aggregation and sintering [51]. High-temperature dehydration causes structural changes in clay minerals, especially in kaolinite-rich lateritic soils [52]. The loss of bound water alters their crystal structure. Soils with lower plasticity indices are more stable and resist deformation under loading. Heat-treated laterites, therefore, have improved engineering properties. This makes them suitable for use in subgrade and sub-base layers in pavement construction.

3.3.4 Specific Gravity Results

The specific gravity (Gs) values show minor fluctuations with temperature changes as seen in Fig. 6.

The specific gravity of **MGA** initially dropped to 2.15 at 100°C, possibly indicating heat-induced mineralogical changes, but increases to 2.8 at 200°C. The ***MGC*** and Yogbo Road soils exhibit a similar trend, with values slightly increasing with temperature. ***MGB*** shows a more stable specific gravity throughout, with a minor rise at 100°C. The response of soil material to elevated temperature shows that the specific gravity of soils can be influenced by factors like mineral composition, particle density, and moisture content as observed by [53].

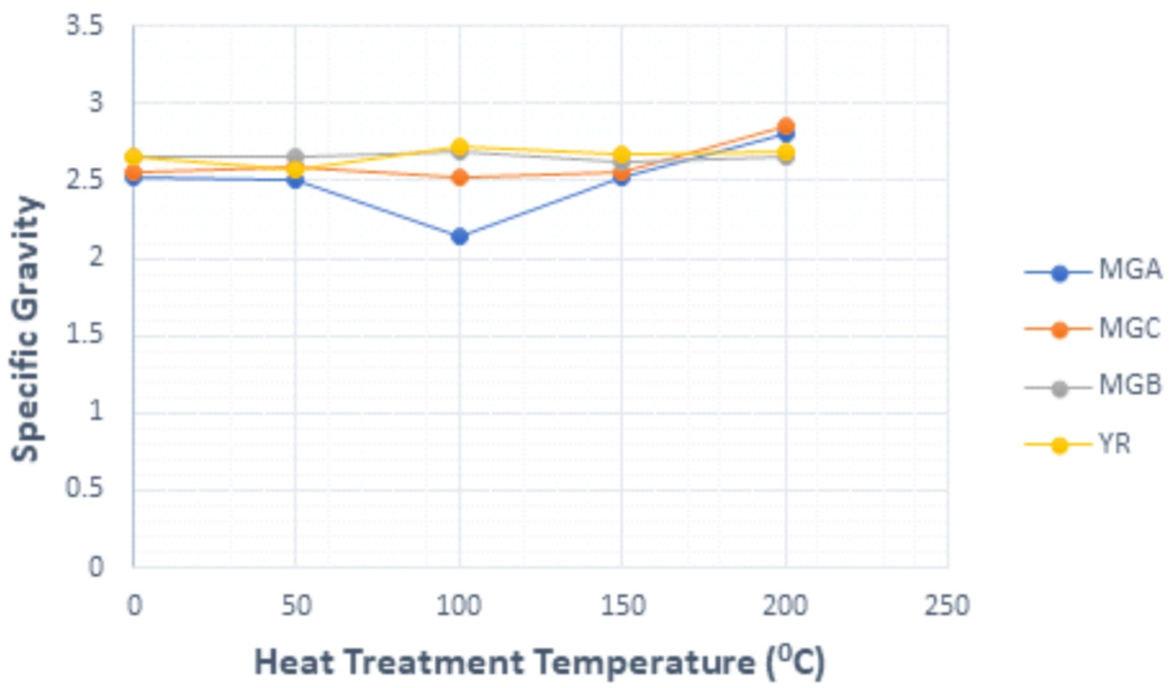

Fig. 6. Variation of Specific Gravity with Heat Treatment Temperature

In heat-treated soils, as the moisture content decreases and mineral transformations occur, the specific gravity may initially drop but can increase as the soil densifies under higher temperatures. These results of specific gravity increasing at higher temperatures in lateritic soils could be due to particle densification and removal of organic matter.

In general, the specific gravity of soil is heavily influenced by its sand content, mineral composition, and formation processes [54]. For the four soil samples analysed, specific gravity values ranged from 2.54 to 2.66, with an optimal value of 2.86 for Yogbo Road sample calcined at 200^{0}C. These values fall within the acceptable range of 2.50 to 2.75 for quality lateritic materials [55], signifying that the lateritic soil samples examined in this study met the required standard.

Furthermore, Roy and Dass [56] highlighted that higher specific gravity improves key shear strength parameters, such as cohesion and the angle of shearing resistance, as well as the California Bearing Ratio (CBR), which are vital for subgrade material performance.

3.4 Compaction Characteristics

The compaction results, specifically Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), provide critical insights into the response of laterite soils to heat treatment. The primary objective of soil compaction is to increase soil density and shear strength while reducing compressibility and permeability. The best results are achieved when field compaction reaches 100% of the Maximum Dry Density (MDD) at the Optimum Moisture Content (OMC), which ensures key improvements in soil properties such as enhanced consolidation and decreased permeability [57].

3.4.1 Maximum Dry Density (MDD) Maximum

Dry Density (MDD) is a measure of the soil's ability to compact under a given energy. Higher MDD values indicate denser and potentially stronger materials. Fig. 7 depicts the trend of soils maximum dry densities in response to heat treatment.

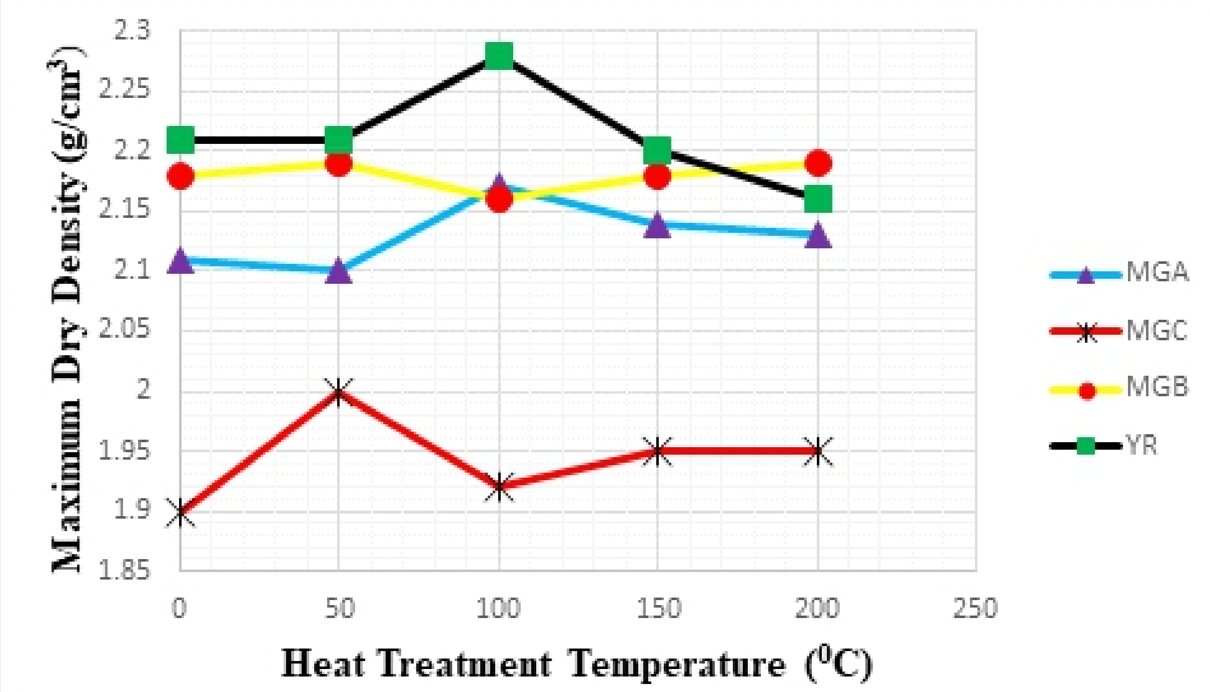

Fig. 7. Variation of Maximum Dry Density with Heat Treatment Temperature

At room temperature (Untreated Soil): The initial MDD values of the untreated soils show significant variation between the different locations. The MDD values for ***MGA***, ***MGC***, ***MGB***, and **Yogbo Road** are 2.11, 1.90, 2.18, and 2.21 g/cm³, respectively. The variation reflects differences in the mineral composition and particle size distribution of laterite soils from these locations, as supported by previous research that points to the strong influence of intrinsic soil properties on compaction behaviour. ***MGC*** soil, with the lowest MDD of 1.90 g/cm³, suggests a soil with higher clay content or finer particles, reducing its ability to compact densely.

At 50°C: The MDD values show slight improvements for ***MGC*** (from 1.90 to 2.00 g/cm³), which could be due to initial moisture loss improving compactability. However, the other locations show marginal changes, with little overall impact from this temperature treatment.

At 100°C: A more significant change in MDD occurs at 100°C, especially for ***MGA*** (2.17 g/cm³) and **Yogbo Road** (2.28 g/cm³) soils. This may be attributed to the calcination of clay minerals, leading to the expulsion of water and structural rearrangement that allows for better compaction. The slight reduction in MDD for ***MGB*** soil (from 2.18 to 2.16 g/cm^3) suggests that excessive heat can cause some soils to lose cohesiveness.

At 150°C and 200°C: Interestingly, the MDD for most of the soils remains relatively constant or decreases slightly beyond 100°C. For instance, ***Yogbo Road*** soil drops slightly from 2.20 g/cm^3 at 150°C to 2.16 g/cm^3 at 200°C.

The overall observed general 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 [58]; [59]. 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. [60].

3.4.2 Optimum Moisture Content (OMC)

Optimum Moisture Content (OMC) reflects the amount of water required to achieve maximum compaction. The relationship between moisture and soil compaction is well-established, with excessive moisture reducing density and insufficient moisture leading to inadequate compaction. Fig.8 illustrates the response of the soil materials to heat treatment in respect of their OMCs.

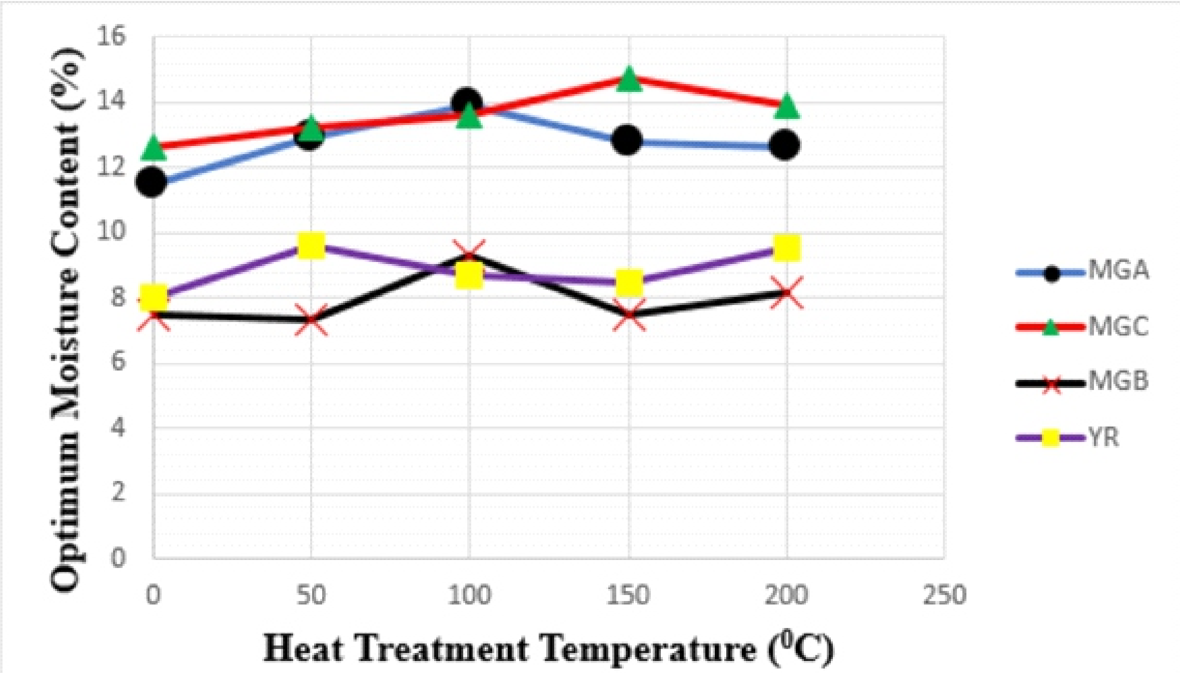

Fig. 8. Variation of Optimum Moisture Content with Heat Treatment Temperature

At room temperature: The OMC of untreated soils varies. **MGC** soil has the highest OMC (12.6%), likely due to its high clay or fines content. In contrast, **MGB** and **Yogbo Road** soils have much lower OMC values (7.5% and 8.0%, respectively), indicating a more granular composition that needs less moisture for optimal compaction. This aligns with Holtz and Kovacs [61]. who noted that soils with more fines generally have higher OMC.

At 50°C and 100°C: Heat treatment affects OMC differently based on soil type. For **MGC**, OMC increases from 12.6% at room temperature to 13.6% at 100°C, possibly due to dehydroxylation of clay minerals, which raises moisture needs. This pattern is consistent with studies on heat-treated soils. In contrast, MGB's OMC drops slightly from 7.5% to 7.3% at 50°C, showing minimal change in moisture requirements with mild heating.

At 150°C and 200°C: OMC values show mixed trends at higher temperatures. **MGC** soil reaches 14.7% at 150°C, continuing its increase in moisture demand for compaction. However, at 200°C, OMC stabilizes or slightly decreases for most soils, suggesting that excessive heating alters the soil structure, reducing moisture requirements.

Overall, the decrease in OMC at higher temperatures may result from improvements in soil properties, such as a reduced diffuse double layer around clay particles, which lowers water retention capacity [62]. Additionally, the reduction in micropores and the development of a more uniformly compacted particle structure during the compaction process at elevated temperatures could also account for the increase in MDD, as proposed by Chen et al. [60]. Variations in OMC could also stem from changes in the hydromechanical properties of soils under thermal treatment, as noted by Afokagboye et al. [59].

3.5 Application to Rural Road Pavement Components Construction

Based on the analysis of maximum dry density (MDD) and AASHTO [63] classification, the soils from ***MGB*** and **Yogbo Road** are the most suitable for use as base course materials in rural road construction. These soils exhibit high MDD values, indicating excellent compaction properties essential for base course layers. ***MGB*** soil has an MDD of 2.18 g/cm³, maintaining this value across different heat treatment levels, while Yogbo Road soil peaks at 2.28 g/cm³ at 100°C. These high MDD values suggest that both materials can withstand significant loads and offer better long-term stability. Additionally, soils from ***MGA***, with an MDD of 2.17 g/cm³ at 100°C, also show good compaction characteristics, making them a viable option for base courses, especially after heat treatment. However, ***MGC*** soil, with a lower MDD of 1.90–1.95 g/cm³, is more appropriate or subbase applications due to its lower compaction capacity as opined by [39].

According to [63] classification, base course materials require high MDD values and low plasticity. The soils from ***MGB*** and Yogbo Road meet these criteria, making them ideal for rural road construction where compaction and stability are crucial. ***MGA*** material, though slightly lower in MDD, still falls within the acceptable range for base courses when heat-treated. In contrast, ***MGC*** soil, with its lower MDD, may not provide the necessary compaction for base courses but is suitable for subbase layers where load-bearing demands are lower thus confirming the findings by Emesiobi [64]. opining that soil with MDD above 2.1 g/cm³ is considered excellent for subgrade, while MDD values from 1.9 to 2.1 g/cm³ are rated good. The Federal Ministry of Works and Housing [47] recommends an OMC of 18% and an MDD of 1.7g/cm³ for pavement materials. Thus, MGB, Yogbo Road, and MGA soils are preferred options for the base course, ensuring durable and sustainable rural road pavement construction.

4.0 CONCLUSIONS

The study demonstrates that heat treatment has a considerable impact on the engineering properties of lateritic soils, specifically by reducing plasticity and improving compaction characteristics. The results indicate the following:

MGA Soil: MGA showed reduced liquid and plastic limits following heat treatment. Its maximum dry density increased at 100°C but showed minor changes beyond this temperature. MGA soil is suitable for subbase and base layers in rural road construction, especially after heat treatment at moderate temperatures (100°C–150°C).

- **MGC Soil**: MGC showed significant improvement in MDD and OMC with heat treatment, making it suitable for subbase layers after heating to 100°C. However, its higher fines content requires careful management to avoid plastic deformation.
- **MGB Soil:** MGB, being the most granular, displayed excellent compaction characteristics both in natural and heat-treated conditions. It is highly suitable for base course

construction, particularly with moderate heat treatment at 100°C.

Yogbo Road Soil: Yogbo Road soil responded well to heat treatment, with increases in MDD and reductions in plasticity at 100°C. It is most appropriate for base and subbase applications, especially in environments where moisture control is critical.

In terms of Atterberg Limits, Guidelines specify that sub-base materials should have a liquid limit (LL) ≤ 30% and plasticity index (PI) ≤ 12%, while sub-grade materials should have an LL < 50% and PI < 30% [43]; [65]. A liquid limit below 30% indicates low plasticity, while an LL of 50% or more indicates high plasticity [66].

In this study, all the heat treated samples show medium plasticity except **MGB**, with liquid limits between 30% and 50%.

Overall, the study concludes that heat treatment up to 100°C significantly improves the compaction characteristics and reduces the moisture sensitivity of lateritic soils, making them more suitable for rural road pavement construction. However, excessive heating (beyond 150°C) offers limited additional benefits and may slightly reduce the compaction potential of some soils.

Moisture Cycles and Soil Stability and Mitigation Strategies

Heat treatment modifies the soil's mineral composition, improving its binding properties. However, exposure to moisture cycles can lead to a loss of these benefits over time due to hydration effects. However, Tropical climates, with alternating wet and dry seasons, influence the stability of lateritic soils. Saturation during the wet season can increase plasticity, reducing the effectiveness of heat treatment, while heavy rainfall may cause erosion and loss of treated soil layers. Proper drainage systems and additional soil treatments, such as using geotextiles or stabilizers, can enhance resistance to moisture-induced damage and improve road durability.

5.0 RECOMMENDATIONS

Based on the results of this research, the following recommendations are proposed:

1. **Heat Treatment for Rural Road Construction:** Lateritic soils should be subjected to moderate heat treatment (up to 100°C) to enhance their compaction and reduce moisture sensitivity. This will lead to more durable and stable road pavements in rural areas.
2. **Use of MGA Soil:** MGA soil is suitable for both subbase and base layers in rural road construction, especially after heat treatment at 100°C. Its compaction and stability improve with heating, making it a viable option for rural infrastructure projects.
3. **Application of MGB and Yogbo Road Soils:** MGB and Yogbo Road soils are highly recommended for use as base and subbase materials, respectively, due to their favorable compaction characteristics and reduced plasticity following heat treatment.
4. **Caution with Excessive Heating:** Heat treatments above 150°C are not recommended, as they do not significantly improve soil properties and, in some cases, reduce compaction potential. The focus should be on moderate heat treatments that optimize soil performance without causing degradation.
5. **Further Research:**
   a) Further studies should explore the long-term field performance of heat-treated lateritic soils to validate laboratory findings
   b) Further study is needed to explore the mineralogical behaviour of heat-treated lateritic soils to understand how changes in clay minerals, crystallinity, and bonding affect their engineering properties. Techniques like **X-ray diffraction** (**XRD**) and **scanning electron microscopy** (**SEM**) could provide insights into how heat alters the soil's plasticity, strength, and water retention. This would

help optimise the heat treatment process for better compaction while maintaining structural integrity, contributing to more sustainable soil stabilisation methods.

6.0 LIST OF ABBREVIATIONS

AASHTO American Association of State Highway and Transportation Officials
MGA Soil Sample collected at Mbaagi at Point A
MGB Soil Sample collected at Mbaagi at Point B
MGC Soil Sample collected at Mbaagi at Point C
MDD Maximum Dry Density
OMC Optimum Moisture Content
YR Soil Sample collected along Yogbo Road

7.0 DECLARATIONS

Availability of Data and Materials

The data sets generated and analysed during the current study are available from the corresponding author upon reasonable request. All materials used in the study are accessible as described in the methodology section.

Competing Interests

The authors declare that they have no competing interests.

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Authors' Contributions

TJ conceived the study, designed the methodology, provided data interpretation and critically drafted and reviewed the manuscript.

MO collected and analysed data, provided revisions to the manuscript.

All authors read and approved the final manuscript.

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