

Geotechnical Properties and Applications of Iron Ore Tailings-Amended Lateritic Soil for Road Construction

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Abstract

The abundance of lateritic soils in Nigeria has made them one of the most used materials for road construction. However, many of these soils exhibit substandard geotechnical properties, necessitating improvements before their deployment in road construction. This study aims to evaluate the geotechnical properties and practical applications of iron ore tailings (IOTs)-amended lateritic soils for road construction. The lateritic soil obtained from a road construction borrow-pit as well as the mixture with IOTs were subjected to mineralogical and geotechnical tests. The lateritic soil contains appreciable amounts of clay (29.1%), fines (52.4%) and sand (46.6%) with a small quantity of gravel (1.0%). Thus, they can be described as clayey sand. In addition, an investigation of its consistency limits indicates that the soil plots above the A-line and classified as highly plastic clay based on their position on the Unified Soil Classification System (USCS) chart. The results of the geotechnical properties indicate a significant improvement in the geotechnical properties of the lateritic soil with the addition of IOT. There was an increase in maximum dry density and California bearing ratio (CBR) with a reduction in the values of liquid limit, plasticity index, linear shrinkage, and unconfined compressive strength. This study demonstrates that the geotechnical properties of the lateritic soil can be modified to fulfil the standard required for utilization as a road subbase and the minimum required can be suitably achieved by mixing about 20% IOTs with lateritic soil.

Keywords:

geotechnical; iron ore tailings-amended lateritic soil; subbase

1. Introduction

Lateritic soils are formed from the intense weathering and leaching of iron and/or aluminium-bearing parent rocks due to alternate wet and dry seasons prevalent in the subtropical and tropical regions of the world (**Basu and Sinha, 2021**). The process of laterization begins with the alteration of primary minerals of the parent rocks to clay minerals with subsequent leaching of the mobile constituents like bases and silica while the oxides of iron and aluminium are retained as residues in the uppermost layers (**Sinha and Basu, 2021**). Thus, the development and properties of lateritic soil profile depend largely on the climatic conditions, parent rock types and the laterization process (**Daramola et al., 2024**). Lateritic soils are abundant in tropical and subtropical regions, and they are commonly utilized for various con-

struction purposes ranging from ancient structures to smooth roads. Moreover, the abundance and general consideration of lateritic soils as good construction materials have been the major justification, due to their utilization for various construction purposes ranging from spectacular ancient structures to smooth roads. On this basis, research has been executed on the determination of suitability for different purposes (**Oyelami, 2017; Daramola et al., 2024**). Similarly, the influence of the factors controlling the formation of lateritic soils on their geotechnical properties has been investigated by various researchers. For example, the influence of the parent rock types on the geotechnical properties of lateritic soils has been extensively investigated (**Adeyemi, 2003; Mesida, 2006; Ngo'o Ze et al., 2019; Basu and Sinha, 2021**). In addition, the effects of climatic conditions on the geotechnical properties of lateritic soils have been documented by a few researchers (**Mvindi et al., 2017**) who emphasized the role of weathering intensity and seasonal variability.

However, lateritic soils derived from charnockite and charnockitic rocks from southwest Nigeria have been

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shown to exhibit unique geotechnical characteristics. As such, the lateritic soils usually contain excessive amounts of fines (clays and silt) commonly characterized by high plasticity levels which can be attributed to the mineralogical properties of their parent rocks. This is due to the lower quartz content, higher proportions of feldspar, biotite and pyroxene content which would yield soils with suboptimal characteristics for engineering applications (Fatoyinbo et al., 2024; Afolagboye et al., 2024). Therefore, they are usually problematic when utilized for road construction as they exhibit geotechnical properties that fail to meet the required specifications for road construction, thereby resulting in road failure and not justifying their huge cost of road construction. However, soils with substandard geotechnical properties are commonly treated through a process termed stabilization to bring them to the required standard. The process of stabilization involves the addition of different organic and inorganic materials, such as lime, cement, bitumen, and even sawdust, to enhance soil properties and render them suitable for engineering applications (Etim et al., 2017; Ojuri et al., 2017; Chompoorat et al., 2019).

Stabilization has helped address several engineering-related problems and improve the sustainability of public infrastructure. For example, Chompoorat et al. (2019) applied cement to enhance the stability of waste soil derived from lakebed deposits, making it suitable for road construction. Also, Chompoorat et al. (2023) utilized cement-treated sands (CTSs) combined with fibre - referred to as cement-treated sand reinforced with fibre (CTSF) - to address the brittle nature of CTS and enhance its suitability as a base and subbase material in pavement and civil engineering structures. Similarly, Chindaprasirt et al. (2021) applied seven distinct types of synthetic fibres to significantly improve the mechanical performance of CTSF for road and pavement applications. Yoobanpot et al. (2020b) combined Ordinary Portland Cement (OPC) with fly ash (FA) to stabilize sediments from bottom of dams for use in construction. The study found that combining FA with OPC provides an effective way of stabilizing dredged sediments for utilization as construction materials. Yoobanpot et al. (2020b) investigated cement fly ash gravel (CFG) columns as an alternative to deep cement mixing (DCM) for embankments on soft clay, demonstrating significantly higher strength and permeability, with optimal performance achieved when 15% of cement was replaced with fly ash. Additionally, Chompoorat et al. (2021b) found that the shrinkage and swelling of OPC-stabilised sediment reduced by as much as 40% and 2.8%, respectively, when 20% FA was added. Chompoorat et al. (2021a) attempted to understand the physicochemical effects of dredged sand through stabilization. It was found, amongst others, that the improvement in the strength and stiffness of the sand is brought about by a series of physicochemical effects, including the hydration reaction, the pozzolanic reaction, flocculation, and agglomeration. More importantly, these findings im-

ply that alternative cementitious composites, like CFG columns, can significantly enhance soil stability and performance - supporting the broader application of iron ore tailings-amended lateritic soils in road construction as sustainable and effective geotechnical materials.

Recent studies have also investigated the stabilization of soils through eco-friendly media and microbial-induced processes in addition to the use of chemical approaches. As an illustration, Chompoorat et al. (2021c) examined the performance of alkali-activated, cement-based controlled low-strength materials (CLSMs). In the study, the CLSM was produced by mixing fly ash, steel slag, sodium hydroxide, and water with bottom ash (BA) aggregate. The findings indicate that the inclusion of slag in a proportion of 10-30% improves the strength of the mix, and higher slag content shortens the setting time and leads to a lower bleeding rate, providing viable perspectives in pavement and other construction applications. Similarly, Chompoorat et al. (2025) explore the use of cup lump rubber (CLR), an agricultural by-product, as a component in CLSM by developing two distinct CLSM mixtures: one based on cement and the other on alkali activation. The study found that some CLSM mixtures, both cement-based and alkali-activated, met the requirements for soil cement bases and subbases. Punmoi et al. (2021) utilized microbially induced calcite precipitation (MICP) in improving the suitability of soft clays for engineering applications. The study found that both vegetative cells and bacterial spores can effectively enhance the strength and modulus of clays by inducing MICP to generate calcite crystals. Similarly, Arpajirakul et al. (2021) applied the MICP technique to improve the engineering properties of soft soil in a sustainable, environmentally friendly, and energy-saving manner. Overall, some materials that have been explored for the stabilization of soils include metakaolin (Muhammad et al., 2020), fly ash (Sharma et al., 2012; Yoobanpota et al., 2020a, 2020b; Chompoorat et al., 2021a, 2021b), tin and gypsum waste (Apriyanti et al., 2019), quarry stone dust (Mishra et al., 2019), coal waste (Mansouri et al., 2021), sand dune (Sharma et al., 2016), palm fibre (Chindaprasirt et al., 2021), amongst others. Notably, these studies consistently demonstrate the prospect for significant improvements in geotechnical characteristics, such as increased load-bearing capacity with a corresponding reduction in plasticity.

Some of the several notable benefits of soil stabilization include the reduction of swelling potential and plasticity, enhancement of bearing capacity, as well as cost savings by significantly reducing the thickness of pavement. Specifically, the stabilization of lateritic soils using cement and lime has been shown to yield significant improvements, as evidenced by enhancements in strength characteristics and reductions in plasticity (Biswal et al., 2018). However, evidence from literature has shown that one key concern with chemical stabilization is the potential toxicity of the treated soils. Thus,

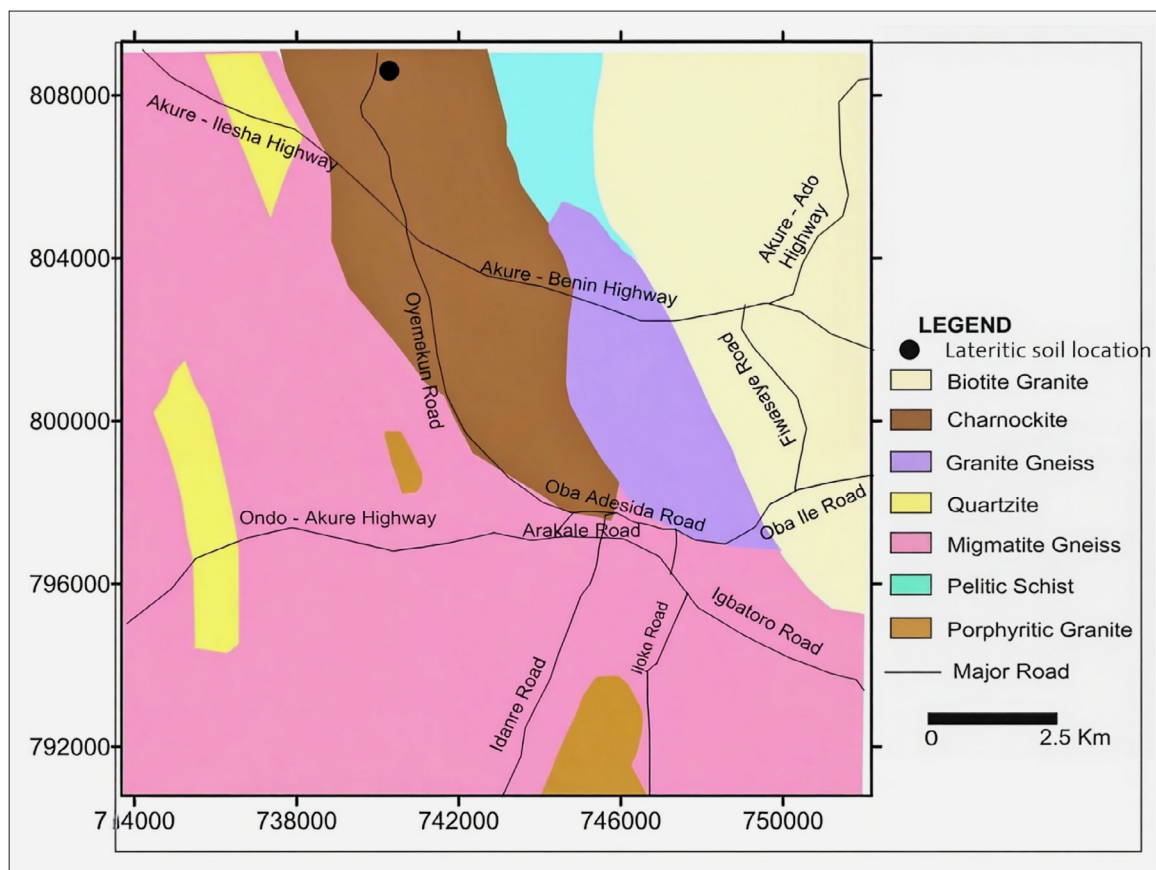


Figure 1. Geology Map of the Study Area (Modified from Falowo et al., 2019)

several studies have investigated assessment of toxicity arising from stabilization, and the potential mitigation techniques. For example, **Leelarungroj et al. (2018)** studied the leaching mechanisms of arsenic, chromium, lead, and zinc from cement and fly ash stabilized soils, and found that chemical compounds (CaO and MgO) on fly ash surfaces can control the pH of the fly ash and soil leachant. Similarly, **Wasino et al. (2019)** investigated phytoremediation with vetiver in relation to heavy metal-contaminated soil and successfully reduced heavy metal contamination in the treated soil. In contrast, **Dontriros et al. (2020)** adopted solidification-stabilization to treat heavy metals arising from municipal-solid-waste-incineration fly ash (MSWI FA), with the study presenting a positive outcome.

Despite the enormous literature on the stabilization of lateritic soils, there is a dearth of research focusing on the stabilization of charnockite-derived lateritic soils. This gap is particularly significant given the challenging geotechnical properties of these soils. Although the utilization of additives such as cement and lime has gained positive results, the costs of incorporating these additives are excessively high and prohibitive. This has turned the attention of researchers and engineers to the utilization of various domestic and industrial waste for stabilization purposes. Prominent among these waste materials are waste generated from mining activities which are com-

monly referred to as mine tailings. The recent efforts to diversify the Nigerian economy have resulted in a sporadic increase in mining activities, as well as an attendant increase in the number of mine tailings generated (**Owolabi and Daramola, 2024**). This study therefore examines the possibility of utilizing some IOTs for improving lateritic soils derived from charnockite for road construction. In doing this, the IOTs were added to the lateritic soils at various mixing ratios. This paper envisages evaluation of the effects of IOTs on the geotechnical properties of the lateritic soils and establishes the appropriate mixing ratio for effective utilization in road construction. This study will be a positive contribution to the effective reuse of mine wastes as a cost-effective alternative to expensive industrially manufactured additives, such as lime and cement for use in highway lateritic soil stabilization. Moreover, the utilization of IOTs will promote the reduction of mine waste, thereby reducing the environmental impacts associated with the storage of mine tailings. Thus, by addressing this issue, road construction materials can achieve enhanced performance, longevity, and sustainability. Furthermore, this research provides a practical solution for enhancing the performance of lateritic soils in road construction and underscores the potential for integrating waste materials into engineering practices, paving the way for sustainable and cost-effective infrastructure development.

Table 1. Summary of the testing program

S/N	Analysis type	Analytical method/category	Standard Used	Sample type	No. of Replicates	Mix Proportions (Soil:IOT)
1	Index Properties	Grain size distribution	British Standard Institution (BSI) (1990)	Air dried	3	100:0, 0:100
2		Atterberg limits	British Standard Institution (BSI) (1990)	Air dried	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:30
3		Specific gravity	British Standard Institution (BSI) (1990)	Air dried	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:31
4	Compaction	Standard Proctor	British Standard Institution (BSI) (1990)	OMC/Max. Dry Density	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:32
5	Strength Tests	UCS	British Standard Institution (BSI) (1990)	7, 14, 28 days curing	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:33
6		CBR	British Standard Institution (BSI) (1990)	Soaked/unsaturated	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:34
7	X-ray fluorescence (XRF)	Major oxide geochemistry		powdered	1	100:0, 0:100
7	X-ray diffraction (XRD)	mineralogical composition		powdered	1	100:0, 0:100

2. Methods

This section of the paper provides a description of the study area. It further presents the method of sample collection, as well as the experimental and analytical techniques used in the analysis of samples collected from the field study.

2.1. Description of sample location

The lateritic soils used in this study are located near Ipinsa town approximately 12 km East of the city center of Akure in southwestern Nigeria (see **Figure 1**). The lateritic soil forms parts of the deposit used as subbase materials and forms the road subgrade of sections of the road linking the city center to Ipinsa Township. Geologically, the area is situated within the Precambrian basement complex province of southwestern Nigeria where the dominant parent rocks are syenite, granodiorites, granites, migmatite charnockite, and quartzite (see **Figure 1**). Specifically, the deposit from which the studied lateritic soil sample was taken is derived from charnockite. The elevation of the area ranges between 372 and 405 m above sea level with dominant gentle slopes which progressively increase in elevation towards the north-western part. The study area lies within the tropical rain forest, characterized by alternating wet and dry seasons with annual rainfall ranging between 1000-1500 mm. Humidity is moderately high in the wet season and low during the dry season. Temperature varies from 21.9°C to 30.4°C throughout the year (**Akintorinwa and Oluwole, 2018**). The vegetation is characterized by thick forest while several stream channels trending approximately east-west and north-south direction flow through the study area.

2.2. Iron ore tailings (IOTs)

The IOTs used in the research were collected from Itakpe, Kogi State, Nigeria. The material was transported in bags to the engineering geology laboratory of the Federal University of Technology, Akure and subjected to various laboratory tests.

2.3. Analytical Methods

The basic index properties including consistency limits, grading characteristics, and specific gravity are determined according to the specifications of the British Standard Institution (BSI) (1990). The soils used for the particle size distribution analysis were carefully soaked with Calgon for twenty-four hours before wet sieving to ensure adequate disaggregation. In addition, geotechnical properties, such as California bearing ratio (CBR), unconfined compressive strength (UCS) and compaction were determined in accordance with the guideline stipulated by BSI (1990). The geochemical and mineralogical properties of the lateritic soil and mine waste were determined by using X-ray fluorescence (XRF) and X-ray diffraction (XRD). The major oxide composition was determined using a Genius IFI Xenometrix XRF. A tungsten Carbide milling pot was used to mill the samples to achieve particle sizes of less than one hundred and fifty microns. Furthermore, the D8 advance diffractometer coupled with an automated flip stick multi-position sample stage was deployed to collect XRD data from the samples at the raw materials research laboratory, in Zairia, Nigeria. The analyses were conducted by means of the standard polystyrene sample holder in θ - θ configuration with exit slit, anti-divergent slit and a Goebel mirror with Ni-filtered Cu radiation ($\lambda = 1.5406 \text{ \AA}$) while the phases were identified and quantified by means of

Table 2. Geotechnical properties of the lateritic soil.

Properties	n	Range	mean	sd	cov
Natural moisture content (%)	3	6.65-6.78	6.71	0.07	0.01
Clay (%) (<0.002mm)	3	29.1-29.4	29.27	0.15	0.01
Silt (%) (0.002-0.075mm)	3	23.2-29.5	23.33	0.15	0.01
Gravel (%) (>4.75mm)	3	1	1.00	0.00	0.00
Sand (%) (0.075-4.75mm)	3	45.4-47.7	46.57	1.15	0.02
Specific Gravity	3	2.65-2.65	2.65	0.00	0.00
Plasticity index (%)	3	30.8-30.9	30.83	0.06	0.00
Liquid limit (%)	3	55.9-56.7	56.33	0.40	0.01
Plastic limit (%)	3	25.3-25.7	25.53	0.21	0.01
Linear shrinkage (%)	3	8.5-8.9	8.70	0.20	0.02
Optimum moisture content, OMC (%)	3	21.2-21.5	21.33	0.15	0.01
Maximum dry density, MDD (Kg/m ³)	3	1909-1912	1910.33	1.53	0.00
Unsoaked CBR (%)	3	20.3-20.43	20.36	0.07	0.00
Soaked CBR (%)	3	12.8-13.2	13.03	0.21	0.02
AASHTO classification	3	A-7-6	A-7-6		
USCS classification	3	CH	CH		

ICDD PDF-4 + Software. Subsequently, the soil stabilized with 5%, 10%, 20%, and 30% IOTs. Afterwards, the mixtures were subjected to basic index and geotechnical laboratory tests to study the effect of IOTs on the properties of the lateritic soil. All the laboratory geotechnical experiments performed followed the specifications of BSI (1990). Each test was carried out three times for each lateritic soil-iron ore tailing mixture to ensure the reproducibility and repeatability of the test results. A summary table outlining the testing program is presented in **Table 1**.

3. Results and Discussion

The results from the field study and laboratory experiments are presented in this section.

3.1. Properties of the Lateritic Soil

The geotechnical properties of the lateritic soil were first examined to establish a baseline for evaluating the effects of iron ore tailings amendment. These properties provide critical insight into the soil's suitability for road construction applications under varying engineering conditions.

3.1.1. Geotechnical properties

The geotechnical properties of the studied lateritic soils are presented in **Table 2** while the distribution of

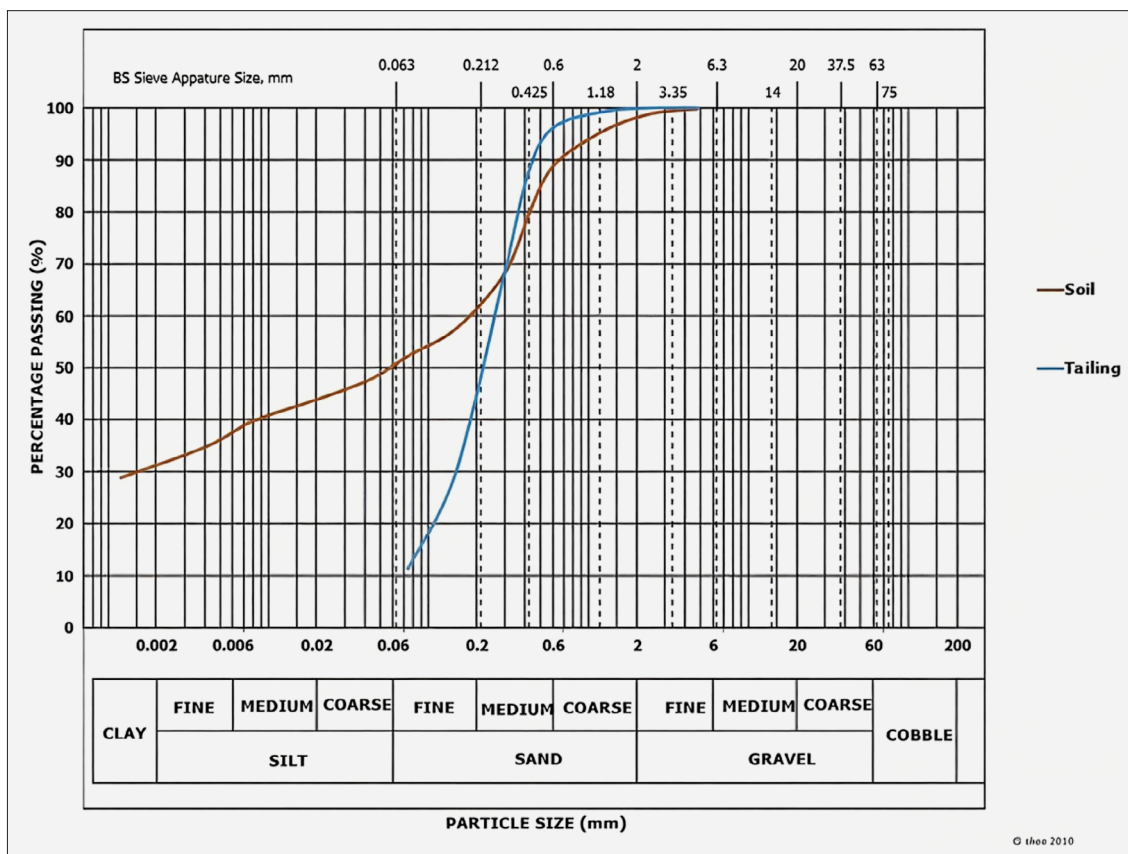


Figure 2. Particle size distribution of the iron ore tailing and lateritic soil.

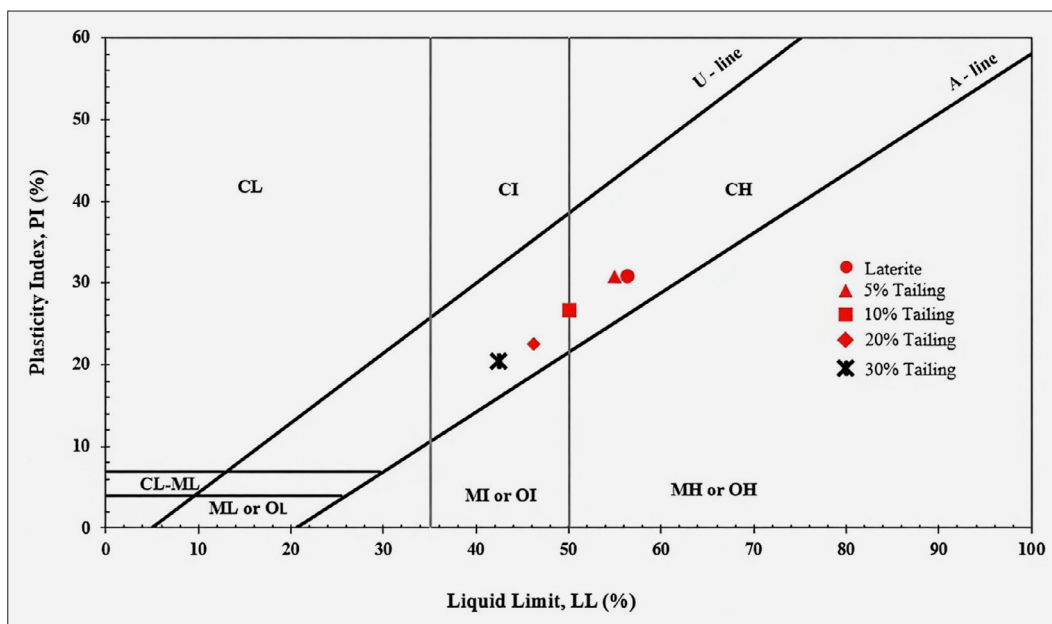


Figure 3. Position plots of the lateritic soil and the various mixes on the plasticity chart.

Table 3. Major oxide composition of the lateritic soil and IOT.

Oxides (wt%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Y ₂ O ₃	Nb ₂ O ₅	K ₂ O	Ag ₂ O	SO ₂	MgO	TiO ₂	P ₂ O ₅	Na ₂ O
Lateritic soils	68.30	7.53	5.57	2.44	2.34	2.33	2.93	2.92	1.33	1.06	0.79	0.78	0.65
IOTs	63.09	16.88	8.35	0.67	1.43	1.06	2.28	1.44	0.93	0.44	2.19	0.28	0.31

the various grain sizes of the raw, untreated lateritic soil is presented in Figure 2.

The soil contains an appreciable amount of clay (29.1%), fines (52.4%) and sand (46.6%) with a meagre quantity of gravel (1.0%). Thus, they can be described as clayey sand. Additionally, an investigation of its consistency limits indicates that the lateritic soil plots above the A-line and classified as highly plastic clay based on their location on the USCS classification chart (Figure 3). The lateritic soils also exhibit a fairly high shrinkage potential according to their linear shrinkage value suggesting that they would exhibit a critical degree of expansion. The soil recorded a maximum dry density, UCS and CBR values which suggest that they possess a good strength characteristic as the UCS value indicates that the lateritic soils could be classified as very stiff. However, a significant decrease in strength is observed as the soil recorded a soaked CBR of 13% implying a 35% reduction in strength. This raises concern and could be a major cause of road failure in the study area as the soaked CBR is significantly less than the specified minimum of 25% recommended for subbase by the Nigerian Ministry of Works (FMWH, 2013).

3.1.2. Geochemical and mineralogical properties of the lateritic soil

The distribution of the major oxide in the lateritic soil investigated is presented in Table 3.

The result indicates that the soil is essentially dominated by silica, alumina and iron oxide which constitute approximately 88 wt% of the tested lateritic soil. In summary, they are classified as a silico-alumino-ferruginous type. Other oxides present in lesser quantities include Y₂O₃, CaO, Nb₂O₅, K₂O and Ag₂O while the rest occur in trace quantities. Additionally, a classification of the soil based on the silica and the content of sesquioxide of aluminium and iron indicates that the soils under consideration are weakly laterized (Oyelami and Van Rooy, 2018; Daramola et al. 2024a). The x-ray diffraction pattern (see Figure 4) indicates that the dominant clay mineral in the soil is kaolinite while the non-clay minerals include muscovite, quartz and albite. Thus, the dominance of kaolinite suggests that they would not exhibit excessive shrinkage and swelling upon intake of water. Additionally, the lateritic soil will tend to demonstrate low to marginal swelling due to wetting and low shrinkage on drying as kaolinite is renowned to exhibit the minimum affinity for water among the different types of clay minerals. In addition, soils with low swelling potential do not crack on drying. This suggests that the lateritic soil will perform well as road construction material, however, the presence of muscovite calls for caution as they are likely to cause field compaction problems.

3.2. Properties of the IOTs

The result of the sieve analysis (see Figure 2) showed that 100 % of the air-dried IOTs passed BS No. 200 sieve

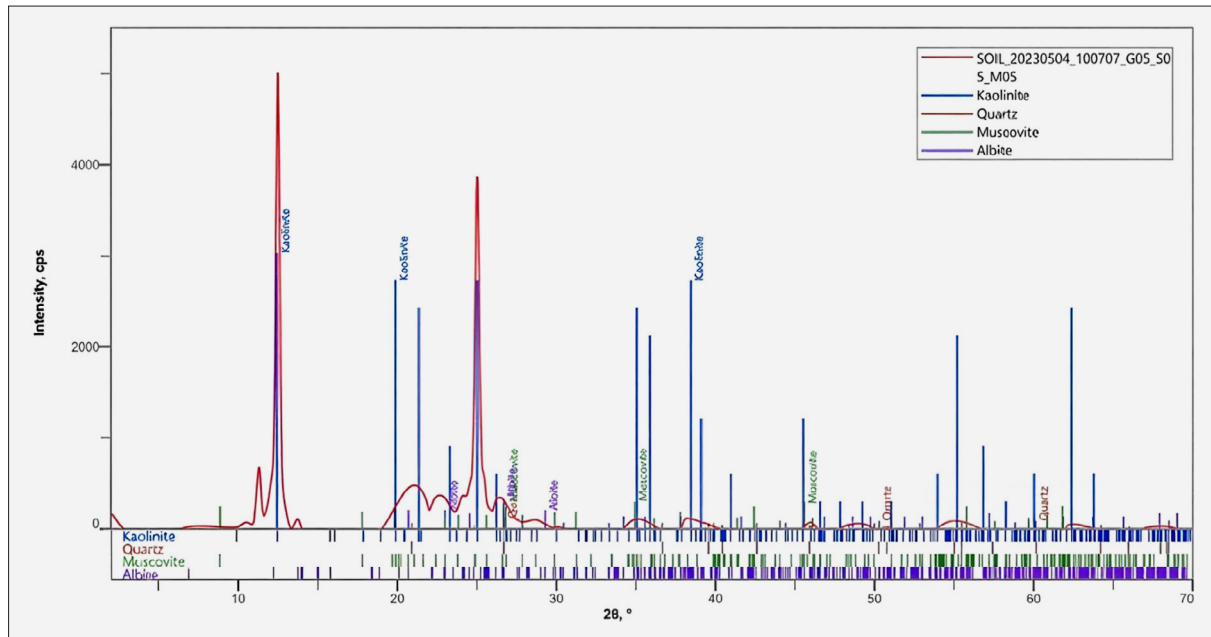


Figure 4. X-ray diffraction pattern of the lateritic soil.

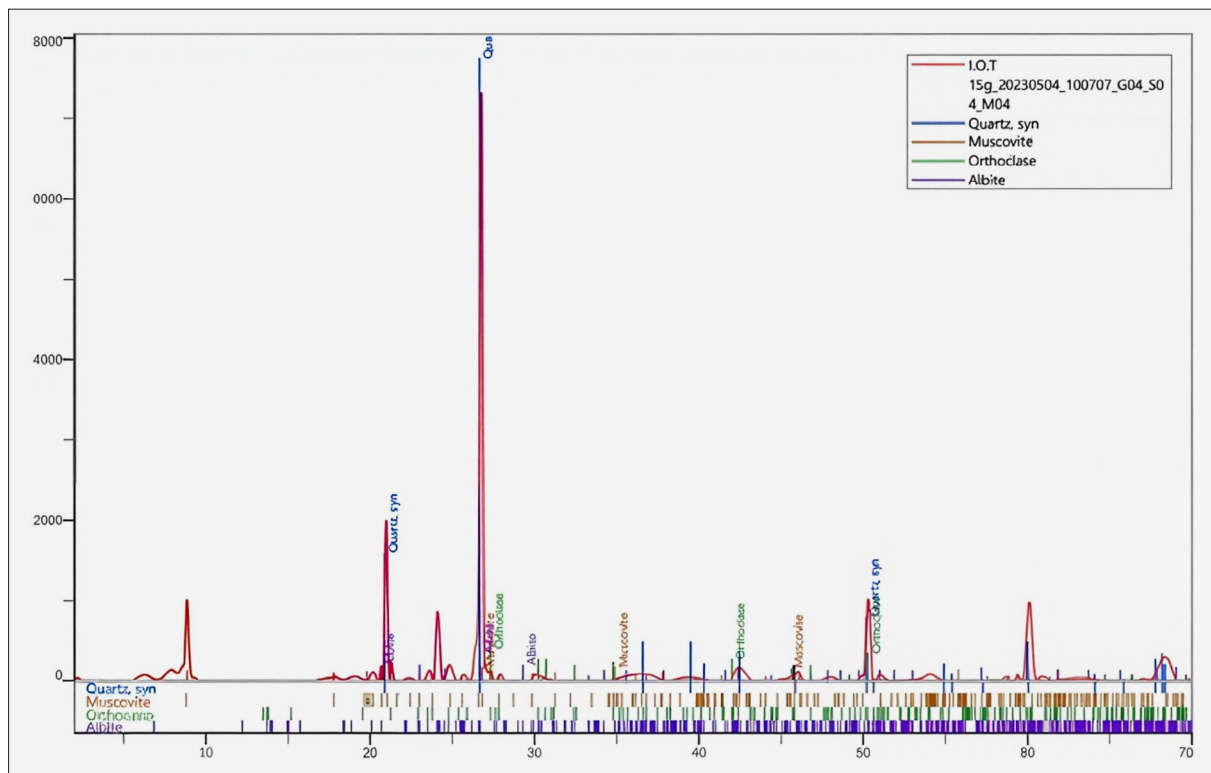


Figure 5. X-ray diffraction pattern of the IOTs.

while they are dominantly made up of sand size particles (90%) with the minor quantity of fines (10%) and as such, they are non-plastic. The oxide composition as well as the properties of the IOTs are reported in **Table 2**. Additionally, their mineralogical composition presented in **Figure 5** reveals that the IOTs are dominantly composed of quartz, muscovite, orthoclase and albite in various quantities. The dominance of sand-size particles

and the absence of deleterious clay minerals indicates that the tailings will not detrimentally shrink and swell within a pavement structure upon intake of water.

3.3. Stabilization

To assess the impact of iron ore tailings on the engineering behaviour of the lateritic soil, a series of stabili-

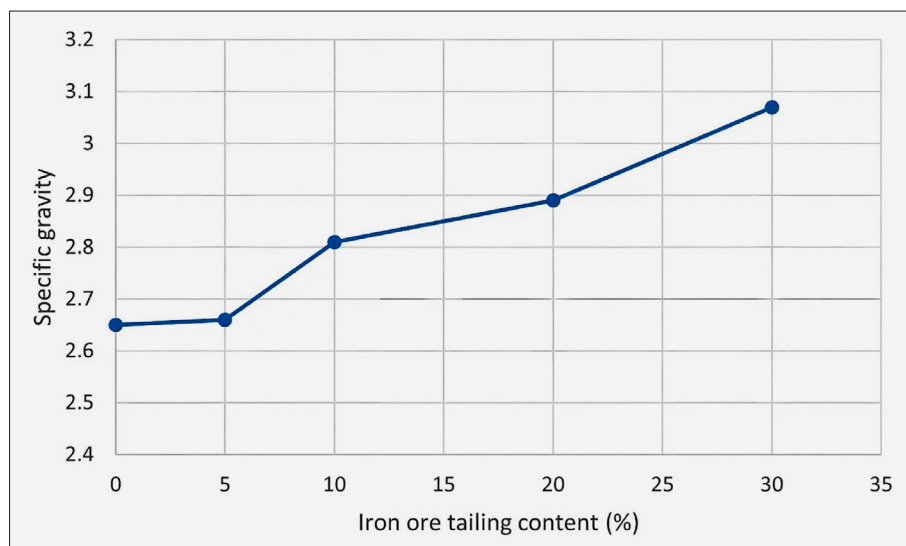


Figure 6. Plot of specific gravity of laterite soil – IOT mixture.

zation tests were conducted. The focus was on key parameters such as consistency limits, compaction characteristics, and CBR, which are essential indicators of soil performance in road construction.

3.3.1. Consistency limits and specific gravity

The consistency limits of the raw lateritic soils as well as the mixtures of soil and tailings (see **Figure 3**) generally depict a reduction with an increase in the tailings content. Specifically, the lateritic soil mixtures containing 10% tailings may be classified as inorganic clays of high plasticity (CH), while the mixtures with 20-30% IOTs are classified as inorganic clays of intermediate plasticity according to the Casagrande classification chart (see **Figure 3**). This implies a reduction in the plasticity characteristics with increased IOT content. This trend is consistent with the observation of previous research on soil-mine tailing mixtures (**Ojuri et al., 2017; Etim et al., 2017; Yohanna et al., 2020**). The general reduction in the liquid limits and plasticity index could be attributed to the increase in the sand fraction which reduces the affinity for water and the expansive capacity of the soil-tailing mixture (**Karakan, 2022; Tanyildizi et al., 2023**). **Figure 6** presents the plots of specific gravities of lateritic soil against IOT concentration. The values of the specific gravity of laterite soil increased from 2.655 to 3.12 when treated with 40% IOT content. This increase may be attributed to the fairly- high value of the specific gravity of the IOT (3.4) compared to that of laterite soil (2.655). A continuous increase was observed for the laterite soil when treated with up to 30% IOT due to the increasing density of the mixtures.

3.3.2. Compaction

The addition of the mine tailing resulted in an increase of the maximum dry density and a decline in organic moisture content according to the moisture-densi-

ty relationships of the soil-tailing mixtures presented in **Figure 7**. Comparable trends were observed in previous investigations on the impact of mine tailings on laterite soils. The maximum dry densities of laterite soils increased from 1910 kg/m³ to 1928 kg/m³, 1936 kg/m³, 1949 kg/m³ and 1955 kg/m³, respectively, with additions of 5%, 10%, 20%, and 30% of the IOTs. Conversely, the OMC reduced from 21.3 % to 20.6, 19.7, 18.9 and to 18.3% respectively with the addition of 5%, 10%, 20%, and 30% of the IOTs with the raw lateritic soils. The increase in the maximum dry densities could be attributed to the higher specific gravity of the grains of the tailings replacing the soil particles, which have a lower specific gravity (2.66). Similar observations were reported in previous studies by **Osinubi et al. (2015), Etim et al. (2017)**, who reported increases in MDD and reductions in OMC when lateritic or clayey soils were blended with iron-rich tailings. Unlike the reduction in MDD and increase in optimum moisture content (OMC) reported by **Champoorat et al. (2021c)** for OPC and FA-treated soils, the present study observed the reverse trend (higher MDD and lower OMC with iron ore tailings addition), underscoring that IOT improves soil compaction mainly through its high specific gravity and filler effect rather than chemical hydration. Additionally, the increased additions of the IOTs reduce the plasticity index, indicating a corresponding reduction in the affinity for water, thereby reducing the optimum moisture content of the mixture (**Afolagboye et al., 2017**). Furthermore, the introduction of the IOTs, which is essentially dominated by fine sands, could have also contributed to the reduction in the organic moisture content due to the tendency to reduce the amount of water held by such a mixture.

3.3.3. CBR

A summary of the results of the CBR is presented in **Figure 8**, where it is apparent that the addition of IOTs to the mixture significantly increases the CBR values.

Figure 7. Compaction curves of the lateritic soils and various mixtures of lateritic soils and tailings.

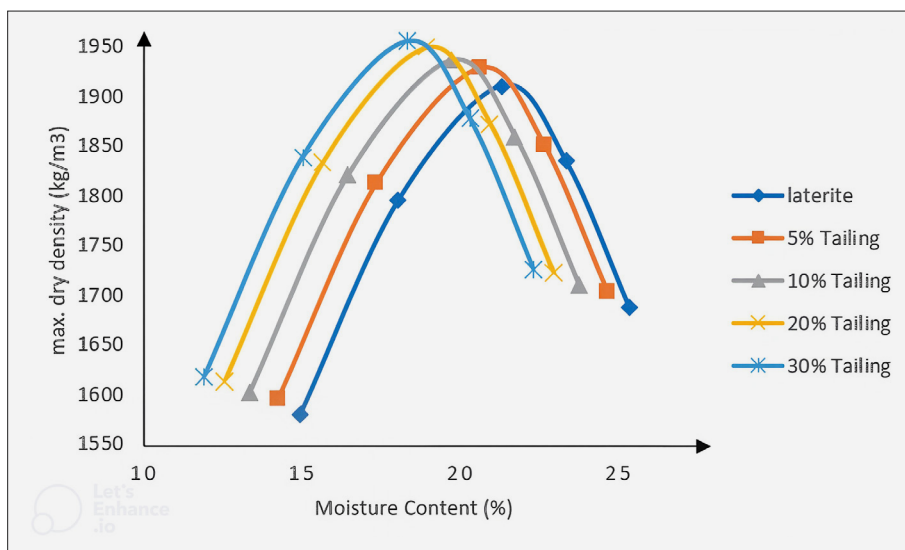
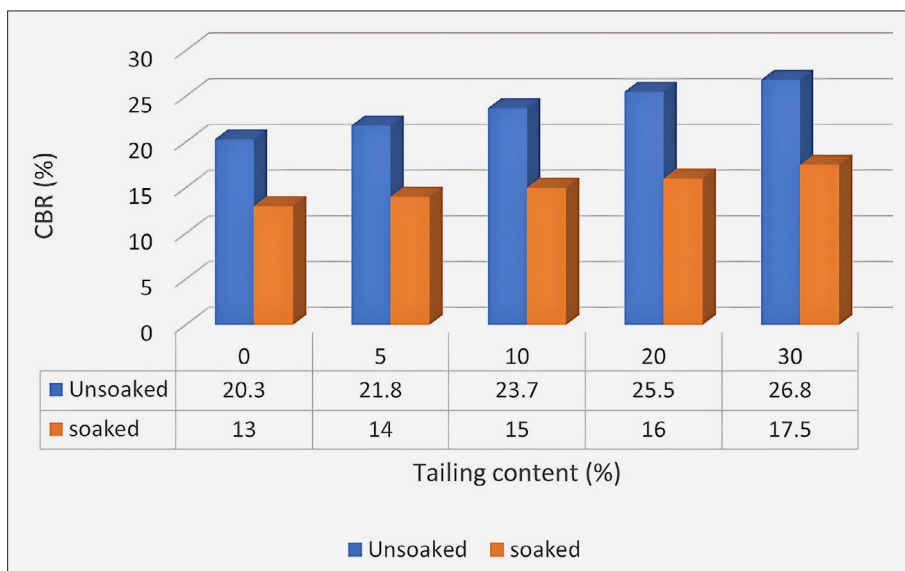


Figure 8. Unsoaked and soaked CBR of the lateritic soils and various iron ore tailing mix.



Similar trends have been reported in some previous studies by **Mohammed et al. (2018)**, **Akinbinu et al. (2022)** and **Ishola et al. (2023)**. The unsoaked and soaked CBR of the lateritic soils were 20.3 and 13 respectively. However, the unsoaked CBR of the mixtures increased to 21.8, 23.7, 25.5 and 26.8 while the soaked CBR increased from 14, 15, 16 and 17.5 upon the addition of 5, 10, 20 and 30% of the IOTs respectively. This signifies an improvement in strength upon the addition of the IOTs suggesting an improved performance when used for road construction. The increase in the CBR values may be attributed to the particle size distribution that improves the compaction and interlocking of soil particles (**Mohammed et al., 2018**). Better grain size distribution often leads to higher density and improved load-bearing capacity which is reflected in an increased CBR. However, despite the general increase in strength as indicated by the CBR, a general reduction in the CBR value was observed upon soaking with the percentage reduction ranging from 34.7 to 37.3%. Thus, careful

consideration should be taken to ensure adequate drainage facilities are provided to impede the ingress of water whenever they are used as construction materials.

3.3.4. UCS

The result of the UCS test is shown in **Figure 9**. The UCS of the IOT-modified lateritic soil samples strikingly decreased with a corresponding increase in the quantity of the IOTs added. The UCS of the raw lateritic soil was 274.1 kPa while the addition of 5, 10, 20 and 30% IOT slightly reduced the corresponding UCS to 256.4 kPa respectively. This represents a percentage reduction of 1.02, 1.39, 1.68, and 6.53% for the uncured UCS.

Previous studies reported by **Akinbinu et al. (2022)** also found a similar trend of reduction in the strength of IOT-amended lateritic soils. In a study by **Chompoorat (2021c)**, the UCS of cement-stabilised soil sediments with 7% and 10% OPC increased with the addition of 25% FA. This finding contrasts with the present study,

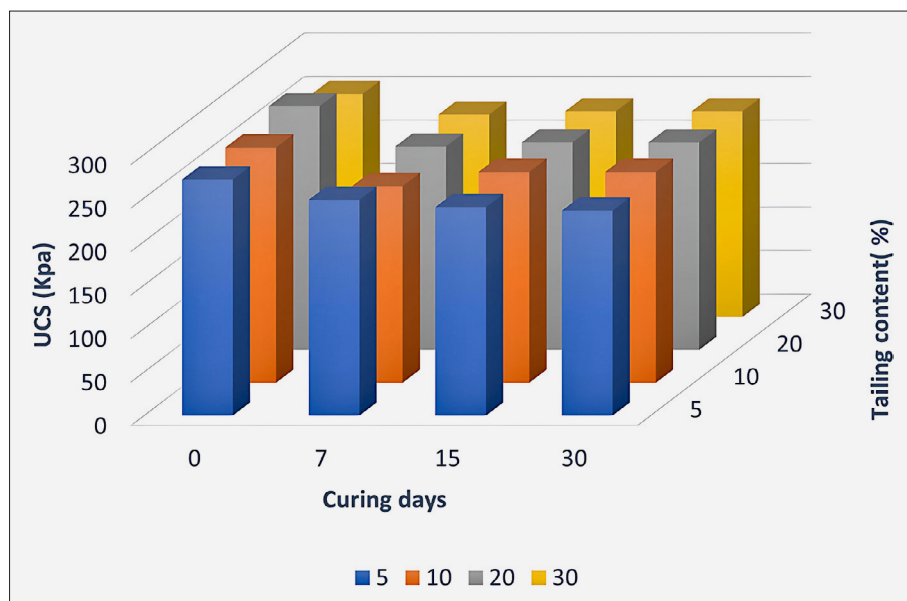


Figure 9. UCS of the lateritic soils and various iron ore tailing mix.

where the UCS of lateritic soil decreased slightly with increasing iron ore tailings content, reflecting the absence of cementitious reactions in IOT compared with the hydration and pozzolanic effects of OPC and FA. The structural change in the soil caused by the presence of IOT can be a plausible explanation for the reduction in strength. Additionally, the IOT may not contribute to higher UCS due to the dominance of sand-sized particles in the IOT. Thus, the reduction in the UCS could be due to a lack of proper bonding between the particles under the compressive load. In addition, the curing of soil mix revealed an initial reduction in UCS, while the UCS value increased after 14 days and showed no significant change after 30 days. A plausible explanation for the initial reduction could be due to the uneven moisture distribution and incomplete chemical reactions. However, moisture redistributes, and the chemical reaction progresses over the next fourteen days, thereby enhancing bond formation and increasing the unconfined compressive strength. Thereafter, significant structural changes stabilize, and no further substantial changes occur for days. This trend reflects an initial adjustment, reaction phases and eventual equilibrium in the properties of the mix during curing.

3.4 Applicability of the Lateritic soil – IOT mix as a suitable material for road construction

The suitability of soils for the construction of roads is significantly determined by their mineralogical and geotechnical properties. Accordingly, various standards and specifications determine the optimal selection of soils for a particular use in terms of index and engineering properties. However, the methods of testing adopted, and the limiting values vary from one country or organization to another, depending on the applications (base or subgrade) and climatic conditions/ material availability and type (Paige-green et al. 2015; Afolagboye et al. 2016). The limiting values specified for the various sec-

Table 4. Specification for road and bridge materials.

Road Layer	Properties of soil	Material specification	Source
Sub-base course	Liquid limit	< 35	FMWH, 2013
	Plasticity index	< 16	FMWH, 2013
	CBR (24 hrs. soaked)	≥ 25	FMWH, 2013
	Linear shrinkage	<8	Madedor, 1983
Base course	Liquid limit	≤ 30	FMWH, 2013
	Plasticity index	≤ 13	FMWH, 2013
	Unsoaked CBR	≥ 80	FMWH, 2013
	% Passing sieve No. 200 (%)	5 – 15	FMWH, 2013
	UCS (kN/m ²)	>103	FMWH, 2013

tions of flexible pavement by the FMWH (2013) are presented in Table 4.

Thus, the properties of the lateritic soils and IOT mixtures were compared with the different specifications (see Table 3) and evaluated by their availability for road construction purposes. The suitability of the lateritic soils and the effects of the IOT on the determined properties for various sections of the highway are discussed as follows.

The untreated lateritic soil contains an excessive quantity of fines, higher plasticity index and lower CBR with respect to the stipulated standard for soils designated for utilization as subbase. Thus, the soils can be adjudged unsuitable for utilization as sub-base and sub-grade based on the properties. This is because the excessive plasticity index and fines content exhibits the tendency to swell. This is corroborated by the classification of the soils into groups A-7-6 of the AASHTO system, which implies poor clayey soil with poor quality as subgrade material. Thus, this underscores the need for thorough stabilization

of the soils with a view to improving its engineering properties. The specific gravity values increased tremendously suggesting that the various mixtures would exhibit a good to excellent performance in road construction as higher specific gravity has been correlated with higher strength (**Daramola et al., 2018**). The addition of IOT to the soils significantly reduced the plasticity index as well as the liquid content of the soils. Thus, it could be noted that there could be a corresponding reduction in the compressibility of the lateritic soils as a high liquid limit usually corresponds to an increase in compressibility. Similarly, the reduction in plasticity index could imply a reduction in the tendency for shrinkage. Furthermore, the addition of IOT reduced the tendency of the lateritic soils to shrink excessively. Specifically, the addition of 30% IOT is required to significantly reduce the linear shrinkage to 7.9%, a value lower than the 8% specified by **Madedor (1983)** for road subbase materials. However, a comparison of the properties of the various mixes with the standard specifications (see **Table 3**) indicated that an addition of 10% IOTs yielded a mix that could be adjudged suitable for utilization as road subgrade. Additionally, an evaluation of the suitability of the mix for utilization as a subbase based on the standard requirement indicates that they are unsuitable for such a purpose.

The maximum dry density of the lateritic soils suggests that both the untreated lateritic soils and the various percentage IOT mixtures are favourable for various construction purposes based on the recommendations of **Aghamelu and Okogbue (2011)**. Additionally, the MDD values recorded by the untreated and treated lateritic soils are notably higher than the minimum recommended by **FMWH (2013)** for use as a road subbase. Also, CBR is one of the most important criteria for the selection of soils in road construction. The CBR values of the treated laterite soils are generally lower than the 80% minimum required for subgrade soil by **FMWH (2013)**. Similarly, the soaked CBR values of the treated lateritic soils are generally less than twenty-five percent. Notably, the soils designated for subbase must fulfil the requirements of soaked CBR greater than 25%. It is worth noting that the untreated lateritic soils initially had a CBR of 13% which fails to meet the required standard specified by **FMWH (2013)**. Thus, the test result indicates that the addition of IOT significantly improved the CBR. While mixed with 20% IOTs, the measured CBR value of the soil mixture is 25.5% thereby fulfilling the minimum material requirement stipulated for the construction of the road subbase. Hence, at least 20% IOT content should be mixed with raw lateritic soil before utilizing it for the construction of the road subbase. The results of the geochemical analysis revealed the absence of toxic metals like Pb, Zn, and Mn. This is consistent with the mineralogy of iron ore tailings, which are dominated by quartz, feldspars, and stable iron silicates, rather than sulfide minerals that commonly host these toxic elements (**Hu et al., 2023; Shen et al., 2023**). Moreover, the reduced quantity of iron oxide can be at-

tributed to its incorporation into aluminosilicate lattices, which reduces its availability in free oxide form and decreases its bulk geochemical signal. This mineralogical characteristic minimizes the risk of heavy metal mobilization thereby highlighting the environmental safety of the reuse of iron ore tailings in road construction. The absence of hazardous trace metals further enhances the sustainability of using IOT in road construction by reducing potential ecological and human health risks while contributing to resilient infrastructure. Generally, the toxicity risks posed by iron ore tailings are lower than sulfide-rich tailings although long-term leaching under acidic conditions can mobilize trace elements (**Dold, 2014; Wang et al., 2023**). **Onyia et al. (2021)** indicated that such risks could be mitigated by employing stabilization strategies such as blending with lime, cement, or pozzolanic additives. Therefore, while the current work establishes the engineering suitability of iron ore tailings-amended soils, future studies should incorporate environmental assessment tests, such as the leaching index to comprehensively evaluate toxicity risks.

From the foregoing, the findings of this study apparently demonstrate that iron ore tailings can be effectively incorporated into lateritic soil for road construction, to enhance their strength and durability while minimizing reliance on natural borrow materials. These findings not only demonstrate the technical viability of IoT-modified soils for road construction but also highlight their sustainability value. As shown by **Leknoi and Likittersuang (2020)**, and **Hong-in et al. (2024)**, the value of simple, cost-effective solutions for sustainable land management in rural communities, the reuse of iron ore tailings as construction material offers a practical pathway to sustainability. By transforming mining waste into a resource for road and infrastructure projects, such reuse supports resilient rural and urban development while advancing SDGs 9, 11, and 12. Reusing iron ore tailings, a major mining by-product, reduces disposal-related hazards and conserves natural soil resources. This apparently enhance pavement durability and lowers the needs for maintenance and its attendant costs, thereby contributing directly to the sustainable development goals of the United Nations in terms of **sustainable communities, resilient infrastructure, and responsible consumption** through the valorization of mining waste. Therefore, the adoption of IOT-amended soils in road construction offers a cost-effective and eco-friendly pathway toward sustainable infrastructure development.

4. Conclusions

This study investigates the geotechnical properties of charnockite-derived lateritic soil and their mixtures with various quantities of IOTs. It further identifies the best lateritic soil- IOTs mixture, which could yield suitable geotechnical properties that conform to the required specification for road subbase. The results demonstrated that the addition of IOTs significantly influenced the geotechnical

properties of the various mixes. The results and evaluation of the geotechnical properties of the soils and IOTs mixtures presented in this study have shown that the geotechnical properties of the lateritic soil can be modified to fulfil the standard required for utilization as a road sub-base. The minimum required can be suitably achieved by mixing about 20% IOTs with lateritic soil. The results of the geochemical analysis revealed the absence of toxic metals like Pb, Zn, and Mn. This is consistent with the mineralogy of iron ore tailings, which are dominated by quartz, feldspars, and stable iron silicates. This mineralogical characteristic minimizes the risk of heavy metal mobilization, thereby highlighting the environmental safety of the reuse of iron ore tailings in road construction applications. Moreover, the absence of hazardous trace metals enhances the sustainability of the utilization of iron ore tailings in road construction by reducing potential ecological and human health risks while contributing to resilient infrastructure. Although, this research establishes the engineering suitability of iron ore tailings-amended soils, future studies should incorporate environmental assessment tests such as the leaching index to comprehensively evaluate toxicity risks.

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SAŽETAK

Geotehnička svojstva i primjena u izgradnji cesta lateritnoga tla poboljšanoga jalovinom od flotacije željezne rude

Velika rasprostranjenost lateritnih tala u Nigeriji učinila ih je jednim od najčešće korištenih materijala za izgradnju cesta. Međutim, mnoga od tih tala pokazuju nezadovoljavajuća geotehnička svojstva, zbog čega je prije njihove primjene u cestogradnji nužno provesti poboljšanja. Cilj je ovoga istraživanja ocijeniti geotehnička svojstva i praktičnu primjenu lateritnoga tla poboljšanoga jalovinom od flotacije željezne rude (IOT) u svrhu izgradnje cesta. Lateritno tlo prikupljeno iz iskopa za cestogradnju, kao i njegove mješavine s jalovinom od flotacije željezne rude, podvrgnuti su mineralnim i geotehničkim ispitivanjima. Lateritno tlo sadržavalo je znatan udio gline (29,1 %), sitnih frakcija (52,4 %) i pijeska (46,6 %) uz manju količinu šljunka (1,0 %), pa se može klasificirati kao glinoviti pijesak. Nadalje, analiza granica konzistencije pokazala je da tlo prema položaju na USCS (*Unified Soil Classification System*) dijagramu leži iznad A-linije te se klasificira kao glina visoke plastičnosti. Rezultati geotehničkih ispitivanja uputili su na znatna poboljšanja svojstava lateritnoga tla dodatkom jalovine od flotacije željezne rude. Utvrđen je porast maksimalne suhe gustoće i CBR (*California Bearing Ratio*) vrijednosti, uz smanjenje vrijednosti granice tečenja, indeksa plastičnosti, linearnoga skupljanja i jednoosne tlačne čvrstoće. Ovo istraživanje pokazuje da se geotehnička svojstva lateritnoga tla mogu modificirati tako da zadovolje standarde potrebne za primjenu u sloju donje podloge kolnika, a minimalni zahtjevi mogu se postići dodavanjem oko 20 % jalovine od flotacije željezne rude u lateritno tlo.

Ključne riječi:

geotehnika, lateritno tlo poboljšano jalovinom od flotacije željezne rude, podloga kolnika

Author's contribution

Sunday Olabisi Daramola (Dr): conceptualization, writing – original draft, investigation and software. **Ayodele Olumuyiwa Owolabi** (Professor): visualization, methodology and validation. **Olushola Daniel Eniowo** (Dr): writing – review & editing. **Hendrik Grobler** (Professor): resources, supervision, visualization and validation. **Moshood Onifade** (Professor): resources, supervision, visualization and validation. **Manoj Khandelwal** (Professor): resources, supervision, visualization and validation.

All authors have read and agreed to the published version of the manuscript.