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Characterization of fly ash stabilized residual laterite

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ABSTRACT

The effective use of residual laterite soils is usually hindered because of their mineralogy and high fines content. This paper studied the potential improvement in the geotechnical and mineralogical properties of fly ash-treated residual laterite collected from Southwest Nigeria. Some physical and geotechnical properties, such as plasticity, compaction, unconfined compressive strength (UCS), and California Bearing ratio (CBR) of untreated and treated laterites were determined using ASTM standard methods. Stabilization was achieved by mixing the laterite with varying proportions (0%, 3%, 6%, 9%, 12%, and 15% by mass of dry laterite) of fly ash. Mineralogical analysis of untreated and treated laterite was done using the X-ray diffractometer (XRD). The results showed a slight initial increase at low proportions of fly ash (at 3%) in the plasticity properties and a subsequent decrease (of up to 65%) afterward. The UCS and CBR of the treated laterite increased over 100% (maximum UCS 110% and maximum CBR 183%) at 6% fly ash content. XRD analysis showed the formation of new minerals, predominantly portlandite, within the stabilized soils. This study confirmed that using fly ash for the stabilization of residual laterite soils is potentially viable for road construction.

Keywords: *California bearing ratio, Mineralogical analysis, Residual tropical laterite, Southwest Nigeria Soil, XRD Analysis.*

1. Introduction

Soil stabilization is the chemical and/or physical processing of soils to improve their engineering properties. It involves also the addition of cementing agents (chemical or non-chemical material) to natural soils and/or the densification of soils to improve some properties of soil [1]. The addition of cementing agents, which usually leads to physico - chemical interaction may be achieved by mixing soil directly with stabilizing material until a homogenous mixture is obtained or by injecting a stabilizer into undisturbed soil [2]. Chemical stabilization improves soil strength by bonding together and/or waterproofing soil particles [3]. Chemical and physical stabilization of soil usually reduce deterioration due to weathering or traffic loading and often reduces the required thickness of bearing layers for road bases and foundations [4].

There are various stabilizing agents including cement, lime, bitumen, or a combination of these. Promoting a cleaner environment by lowering the carbon footprint from cement production has been a major concern for civil engineers [5]. Alternative stabilizers are also available as mostly by-products of industrial or agricultural wastes [6]. Re-use of the waste products produced in large quantities can help in their management. Fly ash (FA) constitutes the majority of waste products from burning pulverized coal in thermal power plants for the generation of electricity and has been successfully used in concrete to improve its durability [7]–[9]. FA is said to be most likely a pozzolan [6]. A pozzolan is any material with little or no cementing value but in reaction with calcium in the presence of water can form cementing compounds. Hence, it can improve the geotechnical properties of poor soils when mixed with or injected into them.

The use of tropical lateritic soils for various construction works, such as pavement, has been extensive [10]–[13]. Factors that have an impact on the engineering properties of tropical lateritic soils and make them unsuitable for construction include parent material, climate, topography, drainage, vegetation, and age [10], [14]. Thus, often there is a need to stabilize lateritic soils before they can be suitable for the intended use. The fact that the FA is a pozzolan makes its utilization for soil stabilization possible. However, the success depends on reactive silica and calcium content [15]. FA is classified into Class C or Class F [1]. Class C FA has adequate free lime content, which is an indication that it exhibits high hydration reactivity in the presence of water [6]. Thus, it is self-cementing and can be used alone for stabilization without additional chemicals [16]. This property also makes it useable as an alternative to ordinary Portland cement (OPC) in most earthen construction [17]. FA of class F can also be used for stabilizing soil with a calcium-rich additive, such as lime, lime kiln, or cement.

The choice of residual lateritic soil used in this study was influenced by the fact that some of the road constructions in Southwest Nigeria usually fail before reaching their design life. Studies, such as [18] and [19], have shown that the soil used for the construction had suboptimal properties. The soil would have been adequate if it had been properly stabilized before use.

Thus, this research investigates the effectiveness of using FA to stabilize marginally poor residual lateritic soil which can be used for sustainable road base pavement construction. This study is significant and relevant for environmental and local economic interests, especially in areas where poor lateritic soils are prevalent as the available construction material.

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2. MATERIALS AND METHODS

2.1. Materials

Lateritic soil used for this research was collected from a borrow pit located along the Ife-Ibadan expressway in Ile-Ife South West Nigeria, at latitude 4°26'57.5''E and longitude 7°29'52.8''N. Fly ash (FA) was prepared at the foundry laboratory of the Department of Materials Science and Engineering, Obafemi Awolowo University, Ile-Ife. The parent coal used to produce the FA was collected from Enugu, Enugu State. It was then incinerated in a furnace at 1000°C. The resulting ash was allowed to cool at ambient temperature in the laboratory temperature over a period of six 6 hours. The FA was then collected and sieved through sieve No. 200 (0.075 mm sieve size) and kept in sealed sacks. The specific gravity of the FA was 2.73.

2.2. Methods

The physical and engineering properties of both un-stabilized and stabilized lateritic soils were determined in the laboratory. The index properties, such as the specific gravity (G) (ASTM D854-02), Liquid limit, LL and Plastic limit, PL (ASTM D4318-00), and particle size distribution (ASTM 98 D422-63) were determined according to the stated standard methods. For compaction tests, the West African compaction method which has an intermediate energy between the standard and modified proctor compaction methods was used. Accordingly, the soil samples were divided into five segments and compacted in a mold with a volume of 2124 cm^3. Each layer was compacted with 27 blows by a rammer of mass 4.5 kg dropped from a height of 450 mm. The optimum moisture content (OMC) and Maximum Dry density (MDD) of the laterite were determined.

California Bearing Ratio (CBR) and Unconfined Compressive Strengths (UCS) of the soil were also determined according to the ASTM D 1883 and ASTM 2000, D2166, respectively. The lateritic soil was stabilized by mixing with varying percentages of FA (3%, 6%, 9%, 12%, and 15%) by dry mass of the lateritic soil. These percentages were selected based on recommendations from previous relevant studies [20]–[22]. The fly ash-soil mixes were carefully prepared to ensure the uniformity of each mix. The UCS and CBR of each specimen were determined at their corresponding MDD and OMC.

A total of 37 experiments were carried out as detailed in Table 1. The standard method and the reason for carrying out the experiments are also detailed in Table 1. The elemental and isotopic composition of both fly ash and lateritic soil were first determined using an X-ray diffractometer (XRD). The XRD analysis was conducted to understand the underlying mechanisms for improvement in the engineering properties of the stabilized lateritic soil. The XRD tests were conducted on the most promising mixtures to establish any change in the chemical compounds of the unstabilized and stabilized soil samples.

Table 1. The detail of caried out experiments.

S/N	Parameters determined	No of experiments conducted	Test specification	Reason for determination
1.	Specific Gravity	6	ASTM D854-02	Soil classification and preliminary analysis
2.	Liquid Limit (LL)	6	ASTM D4318-00	Soil classification and determining the suitability of soil for road construction.
3.	Plastic Limit (PL)	6	ASTM D4318-00	
4.	Plasticity Index	Computed using LL - PL		
5.	Fines content Percent passing sieve No. 40	1	ASTM 98 D422-63	
6.	Optimum moisture content Maximum dry density	6		Moisture density relations determination
7.	California Bearing Ratio	6	ASTM D 1883	To determine the suitability of soil as road material
8.	Unconfined compressive strength	6	ASTM 2000, D2166)	To determine the strength of soil and suitability as construction material
Total of Experiments		37		

3. RESULTS AND DISCUSSION

3.1. Elemental and chemical composition of fly ash and lateritic soil

Fly ash (FA) is derived from the burning of carbonaceous fuel from plant sources (specifically palm kernel shells). These shells are likely to contain silica in their cells, which is absorbed by the palm tree during growth. The XRD spectrum of the FA used in this study, as shown in Figure 1, indicates that its mass is primarily composed of quartz at about 38%, magnetite at about 17%, mullite, and calcite (lime) at about 13%. This result is typical of most fly ash compositions [23]. The presence of mullite indicates high temperature exposure of some of the quartz. These results were similar to those obtained by [6], except that there was no portlandite present in the FA used in this study. The chemical composition shows that the fly ash is class C because the CaO content is more than 10% [16], [24].

The XRD spectrum of the natural soil, as shown in Figure 2, bears all the hallmarks of natural soil in the locale. Of note is the presence of the clay minerals kaolinite (13%) and a small amount of illite (2%). The presence of these minerals is necessary for soils to be stabilized as they serve for binding and holding the other particles together. Among the two minerals, illite may pose construction problems if present in large quantities. The quantity of illite in the present soil was not substantial enough to render any negative effects on the engineering properties of the soil for use as road base material. The other detected phases, such as quartz (55%), calcite (9%), and cristobalite (2%) were the expected minerals in the bulk soil. Notable however is the presence of cristobalite which is a very high temperature phase of quartz and its presence in the soil suggested geologically aged soil. This locale was not known for any recent volcanic activity (for the last several million years); hence the particle of cristobalite was deemed to have weathered from the parent rock.

3.2. Index Properties of Un-stabilized Soil

The index and some mechanical properties of the tropical laterite are presented in Table 2. The Specific Gravity (G) of soil is mainly used to derive other soil engineering properties [25]. The presence of iron oxide concentrated in the coarser fraction of laterite has been attributed to high G in laterite soils. The G of the soil, determined as 2.6 (Table 2), is within the typical range for lateritic soils (Indraratna and Nutalaya, 1991; Fall et al., 1997).

The grain size distribution of the soil revealed that more than 50% of the soil passed through the Number 200 sieve (Table 1), rendering it fine-grained soil according to both the Unified Soil Classification System (USCS) and American Association of State Highway and Transport Officials (AASHTO) classification systems. The liquid limit (LL) of greater than 50% sets the soil in the high plasticity range [26]. The LL and plasticity index (PI) values are plotted below the A line on the plasticity chart (Figure 3), which categorized as silty soil. Thus, the test soil was classified as high plasticity silt (MH) according to the USCS, and as A-5 according to the AASHTO. Such classified soils are rated fair to poor as a subgrade. The specifications set by the Federal Ministry of Works and Housing (1997) for highways require $F_{200} \leq 35\%$; LL ≤ 35%; PI ≤ 12%; and CBRs ≥ 30% for a given soil to be suitable for sub base construction. The plasticity results show that the soil is not suitable in its un-stabilized form as a subbase material; thus, there is a need to improve its properties.

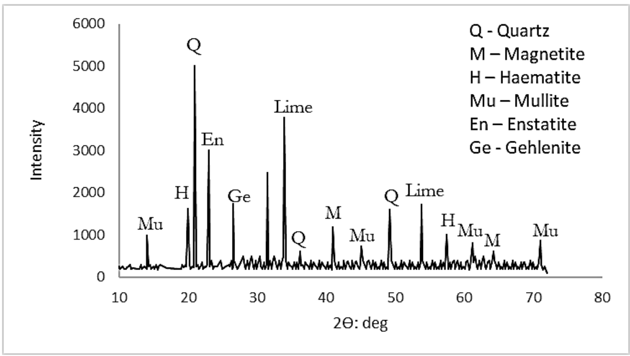

Figure 1: The XRD of fly ash.

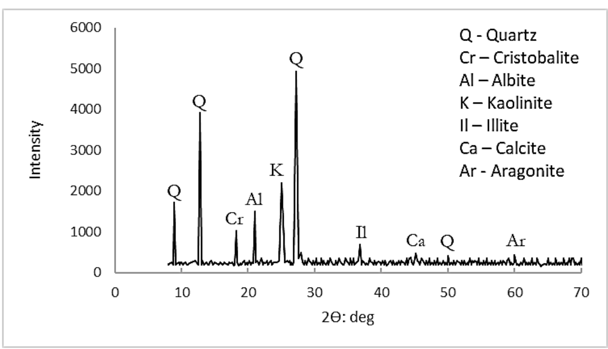

Figure 2: The XRD of un-stabilized lateritic soil.

Table 2. Index and some Geotechnical Properties of Un-stabilized Tropical Laterite Soil.

Properties	Value
Natural moisture content (%)	33.57
Color	Reddish brown
Specific gravity	2.6
Maximum dry density (g/cm³)	1.57
Optimum moisture content (%)	21
Liquid limit (%)	53.4
Plastic limit (%)	45.7
Plasticity index (%)	7.7
Fines content (%)	51.54
USCS Classification	MH
AASHTO Classification	A-5
California bearing ratio (%)	17.8
Unconfined compressive strength (kN/m²)	135.52

3.3. Effect of fly ash on the specific gravity of stabilized soils

The addition of varying percentages of fly ash increased the G of the soil-fly-ash mixes up to 3.00, as presented in Figure 4. G is largely a function of the density of the minerals making up individual soil particles [27], [28]. The increase in G of the mixture up until 9% FA is probably due to the formation of heavier components with ensuing reactions between the active agents in the soil and FA. The decrease in G beyond a critical FA content (i.e. >9%) suggests the depletion of the active agents to form heavier binding compounds and the replacement of heavier soil particles with excess FA in a controlled volume of mixed material.

3.4. Effect of fly-ash on the Atterberg's limits of stabilized soils

The effect of FA on the plasticity of the soil samples is presented in Figure 5a. The liquid limit (LL) of the stabilized laterite generally decreased as the percentages of FA increased. Although, there was an initial increment of about 4% in the LL when the soil was stabilized with 3% fly ash, the LL continued to decrease afterward as the percentage of FA increased. The highest decrease was about 40% when the soil was stabilized with 15% FA. This result is in agreement with the work carried out by [29], where a decrease of up to 70% in LL was recorded for laterite soil. However, similar work on temperate soil by [16] recorded an increase in the LL and PL of FA-treated soil. This outcome indicates that, unlike a temperate soil, tropical lateritic soils possess the natural minerals in quantities necessary to form stabilizing bonds with FA.

The same trend as with LL was recorded for the plastic limit (PL) of the laterite. There was a marginal decrease of about 3% in the PL of the soil when 3% FA was added, but decreased by up to 40% with the subsequent addition of fly ash at 6%. The highest reduction in the PL of about 44% was recorded when the soil was stabilized with 15% FA. The observed trend is contrary to that recorded by [21], [29] where the PL of soil increased as the FA content increased.

As a result of a similar decreasing trend in both the LL and PL of the stabilized soils, only a minor change in the plastic index was observed overall. The largest change occurred with 9% fly ash addition, for which the PI reduced from the initial value of 7.7% to an average of about 2.7%. This is similar to the results obtained by [21], who recorded a reduction in plasticity index from the initial value of 15.3% to an average of about 9.3% at 12.5% fly ash content.

The LL and PI of the stabilized laterite specimens are plotted on the plasticity chart and presented in Figure 3. It can be seen that the plasticity of each of the stabilized soils was altered from high plasticity to low plasticity with the exception of 3% fly ash stabilized soil, as they are all now classified as low plasticity silt (ML).

According to [30], changes in the plasticity characteristics can be explained partly by changes in the thickness of the diffuse double layer of the fines content of the laterite. Additionally, since laterite is rich in iron and aluminium oxides [25], [31], the reactions of these sites on the clay component with the reactive silica from FA, might have led to the formation of cementation products, hence reduced LL and plasticity. [32] found that with increasing FA content, the PI of subgrade soils originally classified as both low and high plasticity clays (CL and CH) reduced. The reduction in the PI of the laterite in the present study was not so pronounced, probably because of its high silt content and lack of enough clay minerals for sufficient reactions to take place at the clay sites.

Regression analysis (at a 95% confidence level) shows that the percentage of FA used had a significant effect on LL, PL, and PI with P values of 0.000538, 0.001013, and 0.01487, respectively. The relationships between measured and predicted Atterberg's limits are presented in Figures 5b-d. The results show that the predicted values are in good agreement with the measured values with a correlation of 85%, 84%, and 89% for LL, PL, and PI, respectively.

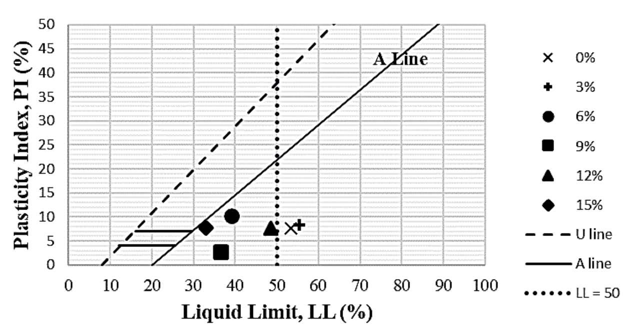

Figure 3. The placement of the plasticity data for the un-stabilized and stabilized laterite soils.

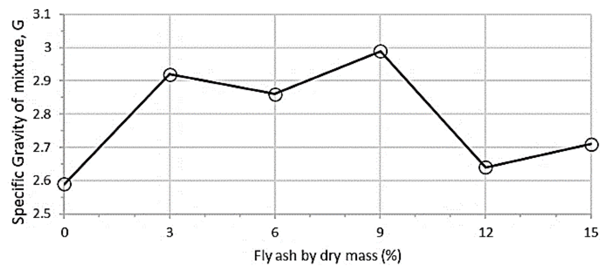

Figure 4. The effect of FA on the specific gravity of the stabilized soil.

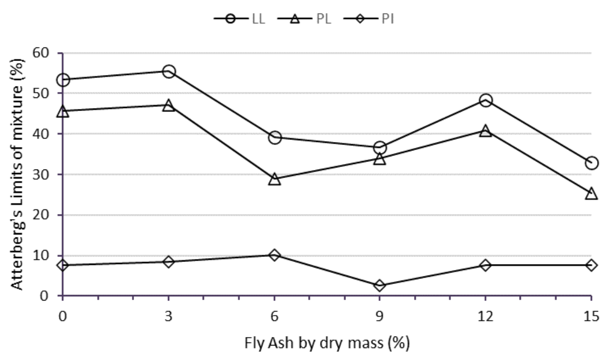

Figure 5a: Atterberg's limits of stabilized soils.

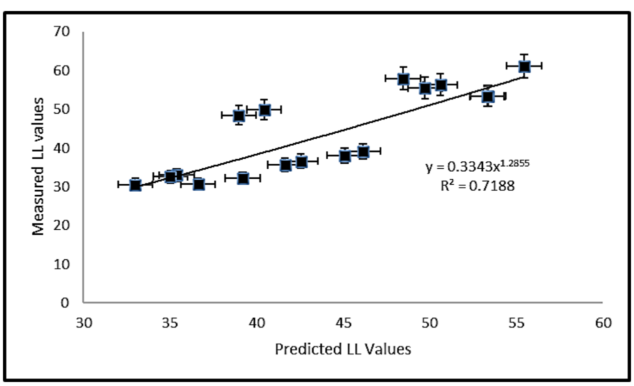

Figure 5b. Measured and predicted LL values.

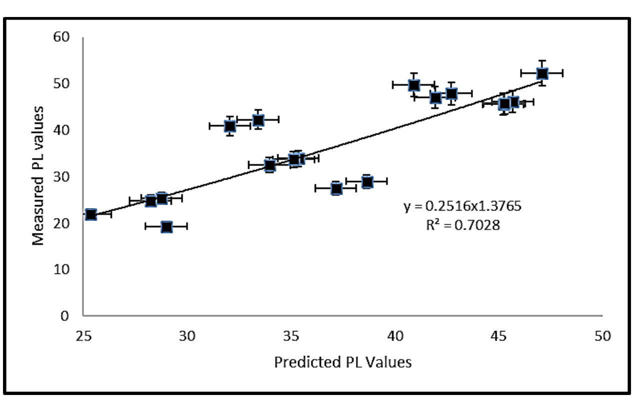

Figure 5c. Measured and predicted PL values.

3.5. Effect of fly ash on moisture density relations

The maximum moisture density (MDD) and optimum moisture content (OMC) of the stabilized soils are presented in Figure 6. It is observed that there were variations in the OMC with increasing FA content. The maximum OMC was 24.5% at 12% fly ash, which constituted about a 17% increase from the initial value. Although the OMC decreased at 3% fly ash content, it increased continuously thereafter at higher fly ash contents. The increase in OMC observed here is contrary to the results of others [21], [32], [33] which recorded a reduction in OMC with increasing FA content. The increase in OMC can be due to the need for hydration for cementitious FA and to release the capillary tension from the exposed surface of the finer FA particles according to [34]. The increase in OMC can also be an indication of soil-fly ash mix requiring more water for proper intermolecular interaction between the soil and FA particles to take place as FA content increased.

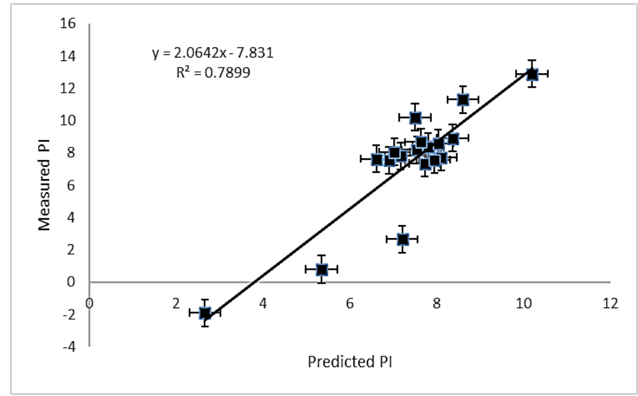

Figure 5d. Measured and Predicted PI.

Figure 6 also shows that the MDD of the stabilized laterite varied as the amount of FA increased. The variation appears to be in the reverse trend of the OMC. There was an increase in the MDD up to 9% FA, measured at 1.84 Mg/cm^3, which constituted about a 17% increase from the initial value. The result of the initial increase in MDD agrees with the findings of others [21], [33]. This initial increase is attributed to FA, which is finer than the soil particles, filling the available pore space upon compaction. The MDD later reduced at 12% and 15% FA content, probably because the increase in FA led to absorption of more water, as evident in the increased OMC. The increased water which is lighter weight than soil simply reduced the mass density by replacement of soil particles. It is noted that [6] also recorded an increased MDD with FA addition. In that study, the FA used had a higher calcium content (67%) that the one used in this study (12.3%).

3.6. Effect of fly ash on CBR

The unsoaked CBR of the stabilized laterite is shown in Figure 7a. It is observed that the CBR of the laterite increased considerably, which is in line with that observed by [21], where they obtained about a 165% increment in the unsoaked CBR as the FA content increased from 0 to 12.5%. An increase in the CBR of stabilized soil is an indication of soil improvement as road base material [35] relative to that of the un-stabilized laterite. The improvement in CBR is due to the pozzolanic reaction that essentially cements the particles together and improves the soil strength properties [36]. The CBR of 17% for the un-stabilized soil reached a maximum value of 48.7% at 6 %FA content. The CBR decreased in excess of 6%FA, but remained above that of the un-stabilized soil. The reduction in the CBR after 6%FA can be attributed to excess FA that was not mobilized in the reaction, which consequently occupied void space within the laterite and counteracted the gained strength. Although there was an increase in all the CBR of stabilized soils, Figure 7a shows that the minimum requirement of 30% by [37] was only satisfied for 6% and 9 %FA stabilized soils.

Regression analysis (at a 90% confidence level) also shows that the percentage of FA is a significant factor affecting the CBR of the treated laterite with p-values of 0.065. The relationship between the measured and predicted CBRs is presented in Figure 7b. The results show that the predicted CBR agrees very well with the measured CBR with a correlation of 83%.

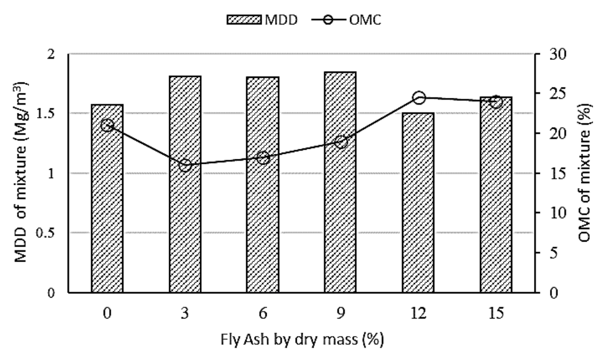

Figure 6. Moisture-density variations of stabilized soils.

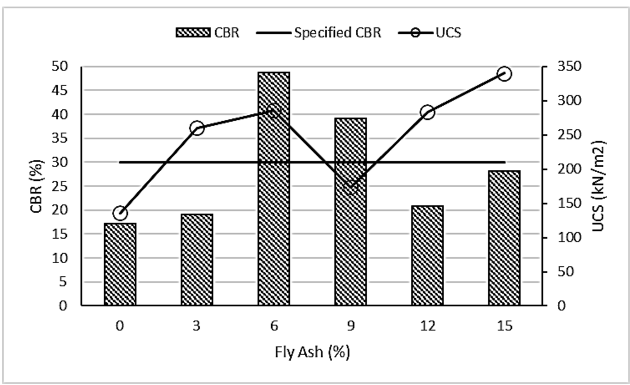

Figure 7a. California Bearing ratios and unconfined compressive strength of the stabilized laterite.

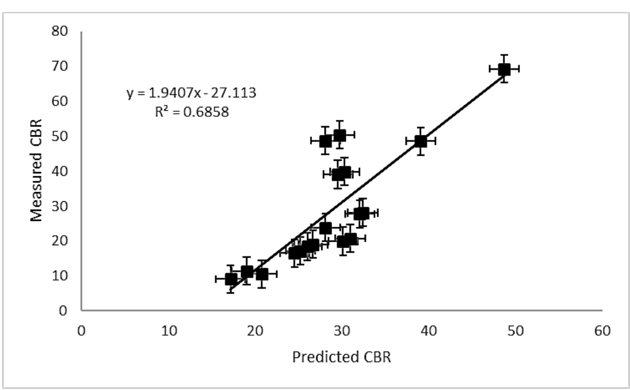

Figure 7b. Measured and predicted CBR values.

3.7. Effect of fly ash on UCS

Unconfined compressive strength (UCS) of the soil-FA mixes at their corresponding optimum moisture contents are presented in Figure 7a. Duplicate specimens were tested for UCS determination, and the average of the results is reported. The addition of FA to the laterite led to an increase in the UCS of all the stabilized soils with an over 150% increase at 15 %FA content. The steady increase is partially attributed to the formation of cementitious gels (hydrates) from the reaction between free lime (CaO) present in the FA and with (alumina) Al_2O_3 and (silica) SiO_2 present in the soil [1]. This led to the agglomeration of particles into a denser formation, causing an increase in strength. This observation is similar to the results obtained by [7]. The increase can also be attributed to the presence of iron oxide which can promote additional agglomeration of soil particles, resulting in higher densification [28]. In addition to the pozzolanic and cementation reactions, the improvement can also be due to the fly ash filling the soil pores as well as the free lime content in the fly ash [38]. The consistency of all the stabilized soils (except for 9% FA stabilized soil) changed from stiff (un-stabilized soil) to very stiff, according to [30].

Regression analysis (at a 95% confidence level) also shows that the percentage of fly ash had a significant effect on the UCS of the treated soil with a p-value of 0.017752. The relationship between measured and predicted UCS values is presented in Figure 7c. The results show that the predicted values agree very well with the measured values with a correlation of 83%.

3.8. XRD Pattern of Stabilized Soils

The results from Atterberg's limits and strength tests show that laterite stabilized with 6% and 15% FA had the most promising results, thus their XRD patterns were determined. The chemical composition of the FA, un-stabilized and optimally-stabilized laterites are presented in Table 2. The XRD patterns for the optimally stabilized laterites are presented in Figures 8 and 9 for 6% and 15 %FA stabilized laterites, respectively. From the XRD analysis, minerals such as, quartz, kaolinite, hematite, calcite, aragonite, feldspar, and illite were identified.

The XRD analysis of 6%FA stabilized soil shows many phases typically associated with soil, including feldspar, hematite (reddish iron oxide), magnetite (black iron oxide) quartz, etc., in various significant percentages. Notably, calcium oxide is absent (CaO). Although CaO was present in the fly ash, it was not detected in the XRD. Its absence may be due to the limit of detection being higher than the concentration of CaO in the 6%FA added to the laterite. The XRD pattern of 15 %FA stabilized soil follows a similar trend as that of 6% stabilized soil. The immediately obvious exception is a slight increase in the concentration of mullite. The mullite is a heat-derived phase from quartz that comes from the FA. The increased concentration is likely due to the overall increase (from 6% to 15 %) of the FA used.

Generally, in comparison with the un-stabilized soil, the XRD patterns of stabilized soils show the disappearance of some peaks and the appearance of new peaks. The new peaks are higher in the 15% FA stabilized soil than in the 6%FA stabilized soil. These results suggest that a phase transformation took place. Some sharp and intense quartz peaks showed up in the stabilized soils. This is possible because of the transformation of amorphous silica to crystalline form with temperature and the addition of FA. It was observed (Table 2) that the illite phase disappeared probably due to the breakdown of the illite structure within the temperature range. There was also the crystallization of hematite. This is similar to what was reported by [39]. The presence of a large proportion of aluminosilicate glassy phase (mullite) in the stabilized soil samples is primarily due to rapid cooling at high temperatures. The alumina to silica ratio of this mullite is about 5:2, and mullite is chemically inert. The XRD patterns of the stabilized soil samples also indicate other crystalline phases, such as hematite (Fe_2O_3) and magnetite. A significant amount of a new mineral, portlandite, was identified within the stabilized soils. It has been shown that the formation of new chemicals, especially portlandite [$Ca(OH)_2$] indicates that a solid and coherent structure was achieved within treated soil [6].

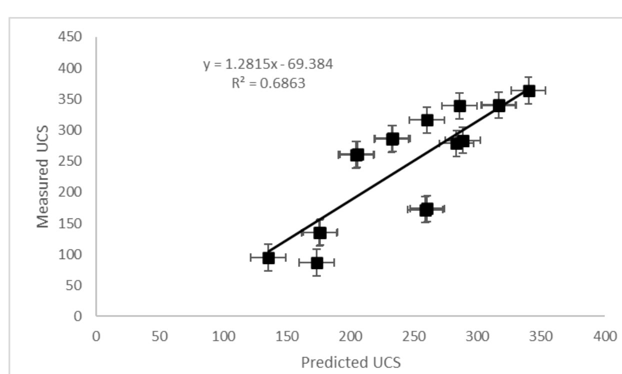

Figure 7c. Measured and predicted UCS values.

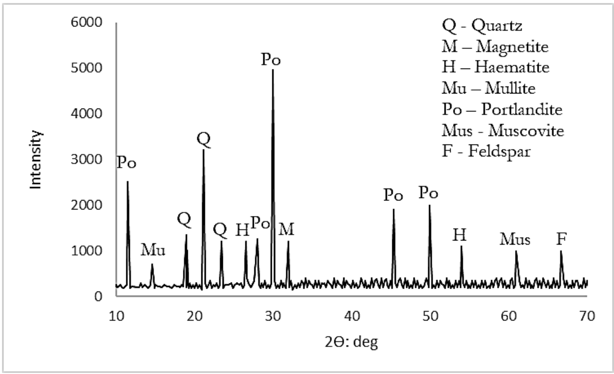

Figure 8: XRD pattern of 6%FA stabilized soil.

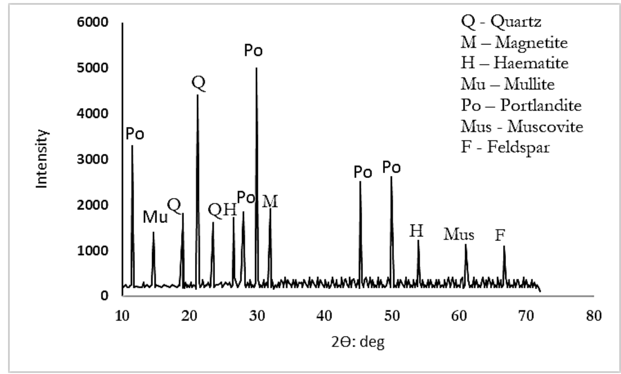

Figure 9. XRD pattern of 15%FA stabilized soil.

Table 2. Some Chemical composition of fly ash, unstabilized and stabilized soils.

Minerals	Chemical composition	Un-stabilized soil	Fly ash	6% stabilized soil	15% stabilized soil
Quartz	SiO_2	55.34	38.03	23.09	26.09
Cristobalite	SiO_2	2.04	-	-	-
Albite	$NaAlSi_3O_8$.	5.67	-	-	-
Kaolinite	Al_2O_3 $2SiO_2{\cdot}2H_2O$	12.63	-	-	-
Illite	$(K, H_3O)(Al,Mg,Fe)_2(Si,Al)4O10[(OH)_2,(H_2O)]$	2.11	-	-	-
Calcite	$CaCO_3$	8.74	-	-	-
Aragonite	$CaCO_3$	9.75	-	-	-
Mullite	$3Al_2O_3{\cdot}2SiO_2$	-	12.93	3.38	4.93
Hematite	Fe_2O3,	-	5.79	6.31	6.36
Magnetite	Fe_3O_4	-	16.81	4.82	3.63
Enstatite	$Fe_2Si_2O_6$	-	8.4	-	-
Gehlenite	$Ca_2Al(AlSi)O_7$	-	3.23	-	-
Lime	CaO	-	12.30	-	-
Portlandite	$Ca(OH)_2$	-	-	51.99	44.86
Muscovite	$KAl_2(AlSi_3O_{10})(F,OH)_2$	-	-	6.48	9.9
Feldspar	$X(Al,Si)_4O_8$	-	-	2.77	3.01

The presence of portlandite can increase strength and improve the durability of any formation. It is believed that the formation of this new mineral is partially responsible for the improvement of the strength properties of the stabilized soils.

4. Conclusion

In this research work, a tropical laterite was stabilized with a class F fly ash, to make it useable as a road material. Based on the conducted experiments and the aforementioned discussions, it can be concluded that (i) the addition of FA to the laterite soil led to reduced plasticity, and increased LL, and PL, thereby the soil classification changed from high plasticity silt MH (for un-stabilized soil) to low plasticity silt, ML (for stabilized soil), (ii) there was an initial reduction in the OMC of stabilized soil with eventual increase as FA contents increased. The increased OMC led to an eventual decrease in MDD at 12% and 15%FA content, (iii) there was an increase in CBR of the stabilized laterite at all FA contents, but only the 6% and 9%FA stabilized soils satisfied the minimum requirement of 30% CBR for soil to be used as sub-base material, (iv) the UCS of all stabilized soils increased as FA content increased, and the consistency of the stabilized soils changed from stiff to very stiff, (v) the mineralogy of the treated soil revealed the formation of new mineral formation, especially portlandite which indicated a solid and coherent structure within the stabilized soil. The results have proven the viability of the use of fly ash as an effective stabilizer for lateritic soil in road construction. This can lead to reduced deterioration/premature failure of subbase soils. The addition of alkaline activation to fly ash stabilized laterite can be explored for further improvement in the geotechnical properties of the soil.

Declaration of Conflict of Interest

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