EVALUATION OF SHEAR STRENGTH OF COMPACTED IRON ORE TAILINGS TREATED LATERITIC SOIL

K. Ishola[1*], T. S. Ijimdiya[2], P. Yohanna[3] and K. J. Osinubi[2]

[1]Department of Civil Engineering, Osun State University, Osogbo, Osun State, Nigeria
[2]Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria
[3]Department of Civil Engineering, University of Jos, Plateau State, Nigeria

Email: isholakzm@gmail.com

ABSTRACT

This paper presents the results of a laboratory study on the evaluation of the shear strength of compacted iron ore tailings (IOT) treated lateritic soil. Lateritic soil used was treated with 0 up to 16% IOT by weight of dry soil. Test performed include index test, compaction (using British Standard Light, BSL and West Africa Standard, WAS energies) and shear strength test. One-way analysis of variance was carried out using Microsoft Excel to determine the level of significance of IOT on the treated soil. The results of the triaxial test show that there is an improvement in the shear strength of soil with the improvement of its shear strength parameters (cohesion and angle of internal friction). Cohesion values decreased from 0 up to 8% IOT content and then increased while the angle of internal friction risen from 0 up to 8% IOT content and then decreased. Also, from the triaxial test carried out with varying cell pressures from 100 to 300 kN/m^2, an increase in shear strength parameters and shear strength were recorded. The shear strength increased in value by 49.79% and 18.15% for BSL and WAS compaction at 8% IOT content, respectively. Statistical analysis carried out on the results using analysis of variance (ANOVA) shows that IOT has a significant effect on the lateritic soil. An optimal blend of 8% IOT improved the shear strength of the soil and can be used for geotechnical engineering applications such as roads and embankments.

Keywords: *angle of internal friction, cohesion, iron ore tailing contents (IOT), Lateritic soil and Shear strength.*

INTRODUCTION

Shear strength of the soil is its resistance to deformation by continuous shear displacement of the soil particles or on masses upon the action of shear stress [1]. This is related to the failure and one of the most important engineering properties of soil. Craig [2] reported that the knowledge of shear strength is required to analyse the stability of soil masses. This assertion prompted geotechnical engineers to study the importance of shear strength in many construction projects such as foundation, retaining walls, earth slopes, and road bases, making its design easier, safe and economical when the soil property is known in the construction site. Ngah and Nwankwoala [3] observed that in recent times, many property developers in Nigeria ignore drastically the role of geotechnical information in the planning, design, construction, operation as well as safety of civil engineering infrastructures. These have failed many engineering structures [4]-[6]. However, most of the structures being constructed required an excavation of the ground before placement. The excavated material is lateritic soil in which its strength properties needed to be known before placing the intended structure.

Lateritic soils are widely used material in many construction projects being a weathered material rich in secondary oxides of iron, aluminium or both. These materials are characterized by greater shear strength properties, chemical resistance, better workability and availability within economic distance in tropical latitudes where they occur in abundance [7]. However, in some cases a swelling clay mineral type containing such as vermiculite, hydrated halloysite and montmorillonite makes their strength not to be guaranteed under wheel load [8]. The reason for these was a result of shrinkage and swelling characteristics, which make it not suitable for road construction [9]. Generally, if lateritic soil does not meet up with the intended purpose specification, it required substances called additives to improve its engineering properties. Several studies [10]-[17] were performed in different countries using additives including bitumen, lime, cement, fly-ash, bagasse ash, cement kiln dust, iron ore tailings, and plantain peel ash to stabilize and improve the construction of a structure on problematic soils.

Iron ore is a rock mineral that is reached in iron oxides with varying colours from dark grey, bright yellow and deep purple to rusty red through which metallic irons are economically extracted and left with tailings. These tailings are produced after the separation of valuable fraction from the uneconomic fraction and causing environmental pollution and seizing of land from being used. However, these drawn attention of industries to its use as a material in many applications such as cement, land reclamation, filling, production of architectural glass, building ceramics and walling materials [18]-[21]. This study was aimed at the evaluation of shear strength parameters of compacted lateritic soil treated with iron ore tailings for use as a road pavement material or embankment applications.

MATERIALS AND METHODS

Materials

Lateritic Soil

The soil used in this study is a naturally reddish-brown lateritic soil obtained by the method of disturbed sampling from a borrow pit in Shika area of Zaria (Latitude 11°15′ N and Longitude 7°45′ E), Nigeria. A study of the geological and soil maps of Nigeria revealed that the soil belongs to the group of ferruginous tropical soils derived from acid igneous and metamorphic rocks by Akintola [22] and the soil map of Nigeria by Areola [23] respectively. Previous studies on soils from this area have been shown to contain kaolinite as the dominant clay mineral. The soil is classified as A-7-6(11) according to the American Association of State Highway and Transportation Officials (AASHTO) [24] soil classification system and medium plasticity clay (CL) according to the unified soil classification system, (USCS) [25].

Iron Ore Tailings

The iron ore tailings (IOT) used in this study were collected from the National Iron Ore Mining Company, Itakpe in Kogi State, located in the north-central part of Nigeria. It supplies the steelworks of Ajaokuta and Aladja as well as producing ore for export. The IOT was passed through No. 200 sieve and mixed with the lateritic soil in the appropriate concentrations. The oxide composition of IOT was determined by X-ray fluorescence (XRF) analysis as shown in Table 1.

Methods

Index Properties

Laboratory tests were conducted to determine the index properties of the natural lateritic soil and iron ore tailings mixtures, in according to the British Standards Institute index for the lateritic soil treated with IOT [26]-[27]. The soil was compacted at the energy levels of British Standard Light (BSL) and West Africa Standard (WAS). A summary of the soil index properties is presented in Table 2. Samples of the soil were treated with 0, 2, 4, 6, 8, 10, 12, 14 and 16% iron ore tailings by dry weight of soil.

Compaction

All the compactions involving moisture-density relationships and shear strength parameters were carried out using energies derived from the British Standard Light (BSL) and West African Standard (WAS). The BSL compactions were carried out using energy derived from a rammer of 2.5 kg mass falling through a height of 30cm in a 1000 cm^3 mould. The soil was compacted in three layers, each receiving 27 blows. The WAS compaction was carried out using energy derived from a rammer of 4.5 kg mass falling through a height of 45 cm in a 1000 cm^3 mould. The soil was compacted in five layers, each layer receiving 10 blows.

Shear Strength Parameter

A cylindrical specimen was extruded from samples already compacted in 1000 mm^3 mould at their respective optimum moisture contents corresponding to BSL and WAS compaction energies to determine shear strength parameters. The extruded specimen was trimmed to the size 38.1 mm diameter by 76.2 mm length and subjected to direct stresses acting in three mutually perpendicular directions in the watertight triaxial apparatus, without prior curing. The axial stress applied to the sample through the spring of the apparatus was increased continuously while the cell pressure was kept constant until the soil failed. The reading of the dial gauge was taken at failure. The major principal stress (σ) was derived from the applied vertical load while the other two principal stresses σ_2 and σ_3 ($\sigma_2 = \sigma_3$) were applied in a horizontal direction by the water pressure around the specimen in the Perspex cylinder until the cylindrical specimen sheared or deformed. Cell pressures were maintained and monitored at 100, 200 and 300 kN/m^2 for the respective three number specimens of each soil sample. Mohr circles of diameter $\sigma^1 - \sigma^3$ for each test were plotted on a shear-stress graph from which cohesion (c) and angle of internal friction (φ) were determined.

Compressive Shear Strength is given by

$$\delta = \frac{\{R.C_R(100-\varepsilon)100kN/m^2\}}{100A} \quad (1)$$

Where, ε = % percentage strain, R = Load ring reading at strain ε. (kN), C_r = Mean Calibration of load ring. (kN), A = Initial cross-sectional area of specimen and (m^2), δ = Compressive Stress at Strain ε. (kN/m^2).

Shear strength of soil was obtained by Coulomb equation which is given as

$$S = C + \delta Tan Ø \quad (2)$$

where, S = Shear strength (kN/m^2), C= Cohesion (kN/m^2), δ = Compressive Stress at Strain ε. (kN/m^2), Θ = angle of internal friction(degree)

RESULTS AND DISCUSSION

Properties of Materials Used

The index properties of the natural lateritic soil show that it is an A-7-6(11) soil, according to the AASHTO [24] and medium plasticity clay (CL) using the USCS [25]. The predominant clay mineral is kaolinite. The oxide compositions of the materials used are summarized in Table 1. Based on the concentrations of the oxides of silicon, aluminium, and iron, the IOT used can be classified as a class N pozzolana in accordance with ASTM C618-78 [28]. The properties of the natural soil are summarized in Table 2, while its particle size distribution curve (PSD) is shown in Figure 1. From the PSD graph, it was observed that 58% of natural soil passed through sieve No 200, which exceeded not more than 35% specified by the Nigerian General Specifications for subgrade material in road construction.

Table 1 Oxide compositions of iron ore tailings and lateritic soil

Oxide	Concentration (%)	
	Iron Ore Tailing	Laterite
CaO	0.607	0.28
SiO_2	45.64	35.60
Al_2O_3	47.70	24.0
MnO	0.067	0.067
TiO_2	0.240	-
K_2O	0.067	-
PbO	0.415	-
Na_2O	0.405	-
MgO	0.393	-
SO_3	-	0.85
LOI	3.0	14.60

Table 2 Properties of the natural and iron ore tailings treated lateritic soil

Property	Iron Ore Tailing (%)								
	0	2	4	6	8	10	12	14	16
Liquid Limits % (w_L)	43.4	46.2	44.4	43.8	42.3	42.7	41.4	41.3	40.2
Plastic Limits % (w_p)	21.3	24.8	27.4	28.9	29.4	27.4	26.7	25.7	23.54
Plasticity Index %(I_p)	22.1	21.4	17.0	14.9	12.9	15.3	14.7	15.6	16.7
Linear Shrinkage %	11.4	11.8	11.9	12.1	12.3	12.6	12.8	13.5	14.3
Percentage Passing No 200 Sieve	58.8	58.0	57.8	53.3	51.6	51.8	51.7	52.2	51.6
AASHTO Classification	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6
Group Index (GI)	11								
USCS Classification	CL	CL	CL	CL	CL	CL	CL	CL	CL
Specific Gravity (SG)	2.59	2.63	2.8	2.9	3.04	3.11	3.27	3.26	3.27
MDD, Mg/m^3	1.72	1.73	1.74	1.76	1.74	1.73	1.72	1.72	1.71
OMC, %	16	17.5	18	18.5	18	17.5	17.2	16.5	15.8
BSL Compaction									
Cohesion (kN/m^2)	100	70	60	50	40	60	80	90	110
Angle of Internal friction (°)	17	18	19	20	22	19	17	15	13
WAS Compaction									
Cohesion (kN/m^2)(C)	140	130	120	110	90	100	120	135	150
Angle of friction (°)	19	21	23	26	28	26	22	19	16

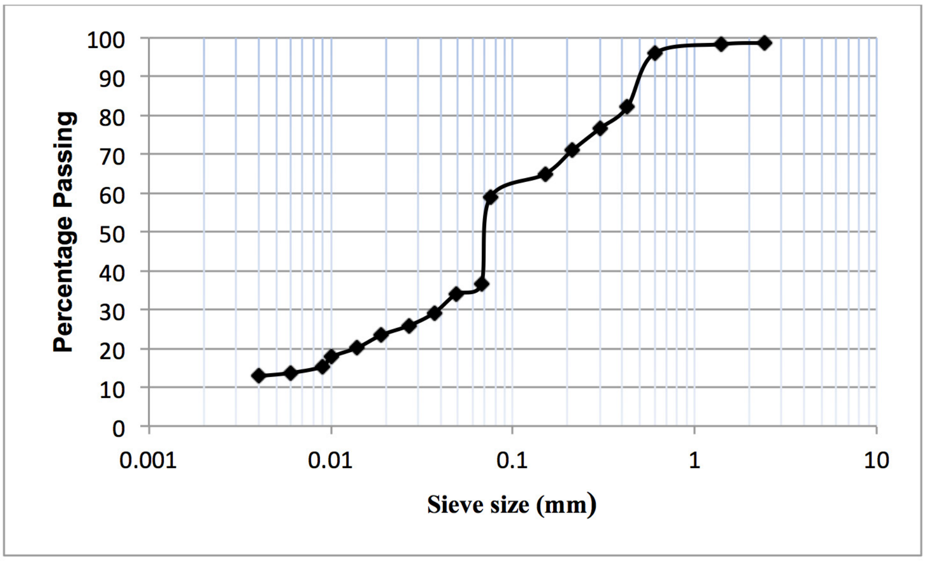

Figure 1 Particle size distribution curve of the natural lateritic soil

Compaction Test Result

The traditional compaction curves of dry unit weight versus moisture content corresponding to BSL and WAS compactive effort for the soil mixtures (0% and 8% IOT content) are reported in Figures 2 and 3 respectively. The curves for the treated specimens are similar to the curve for untreated samples. The addition of IOT resulted in an increased maximum dry unit weight. However, it was observed that optimum moisture content increased with higher IOT content due to the water needed for IOT-lateritic soil interaction [30].

Shear Strength Parameters (Cohesion "C" and Angle of Internal Friction "Φ")

The variation of shear strength parameters of lateritic soil iron ore tailings mixture was depicted in Figures 8 and 9. The Mohr-Coulomb shear strength enveloped for the natural soil (0% IOT) and 8% IOT treated lateritic soil for British Standard Light and West Africa Standard are shown in Figures 4, 5, 6 and 7 respectively. 8% of IOT treated soil gives the external shear strength envelope.

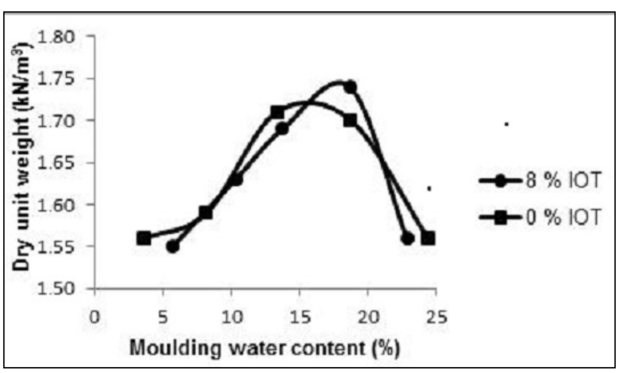

Figure 2 BSL compaction curves for soil mixture containing 0% and 8% of IOT

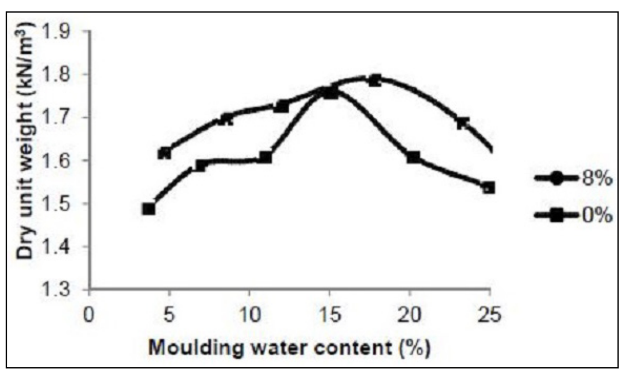

Figure 3 WAS compaction curves for soil mixture containing 0% and 8% of IOT

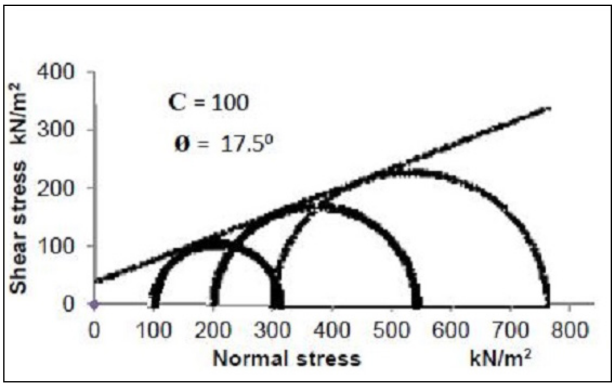

Figure 4 BSL Mohr Plot for 0% IOT treated lateritic soil

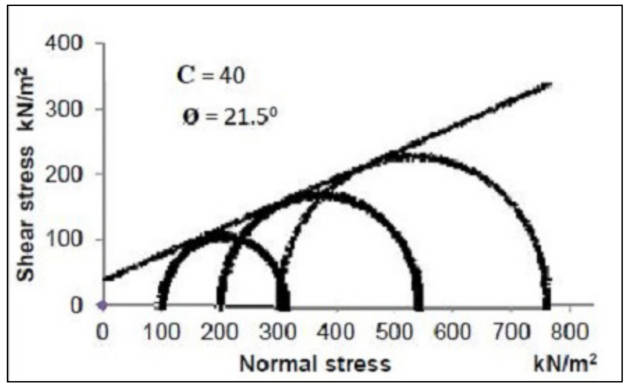

Figure 5 BSL Mohr Plot for 8% IOT treated lateritic soil

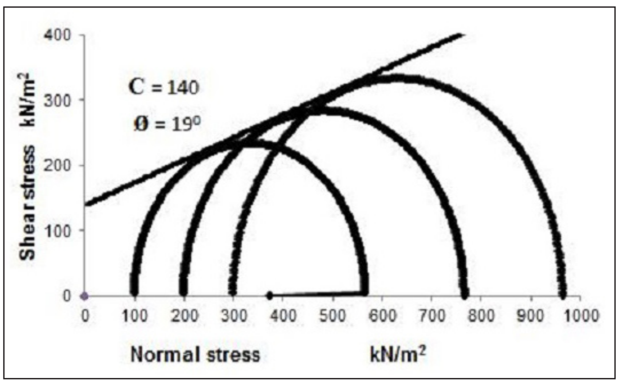

Figure 6 WAS Mohr Plot for 0% IOT treated lateritic soil

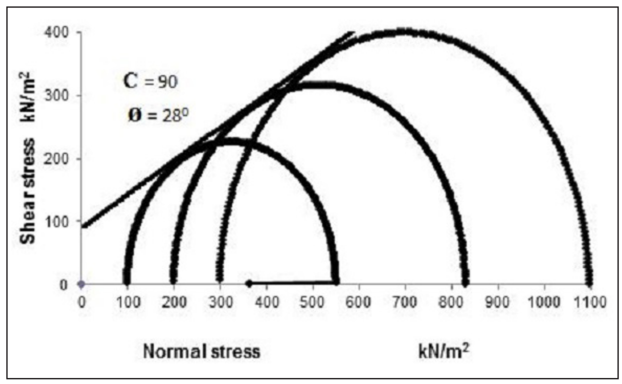

Figure 7 WAS Mohr Plot for 8% IOT treated lateritic soil

Cohesion

Test results of cohesion of IOT treated lateritic soils when compacted with BSL and WAS energies is presented graphically in Figure 8. Generally, the cohesion of the lateritic soil initially decreased to a minimum and then increased with higher IOT content. For the natural lateritic soil of sample compacted with BSL energy, cohesion initially decreased from 100 kN/m^2 to 40 kN/m^2 at 8% IOT content and increased with higher IOT content. A similar trend was recorded for WAS compaction as cohesion decreased from 140 kN/m^2 for the natural lateritic soil sample to a minimum value of 90 kN/m^2 at 8% IOT content and increased with higher IOT content to 150 kN/m^2 at 16% IOT content. The decrease in cohesion with higher IOT content agrees with the findings reported in many research [31]-[33]. The decrease in cohesion could be attributed to the clay fraction reduction due to the ion exchange reaction between the calcium ions from the IOT and clay minerals, which flocculated and agglomerated the clay particles to form coarser fractions, thus reducing the number of fines.

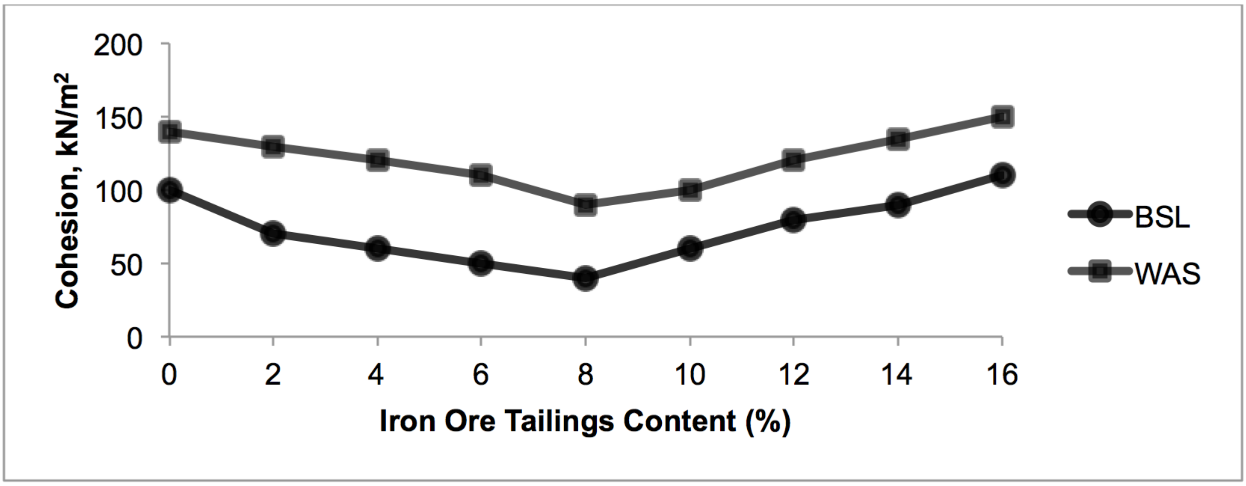

Figure 8 Variation of cohesion of lateritic soil with iron ore tailings content angle of internal friction

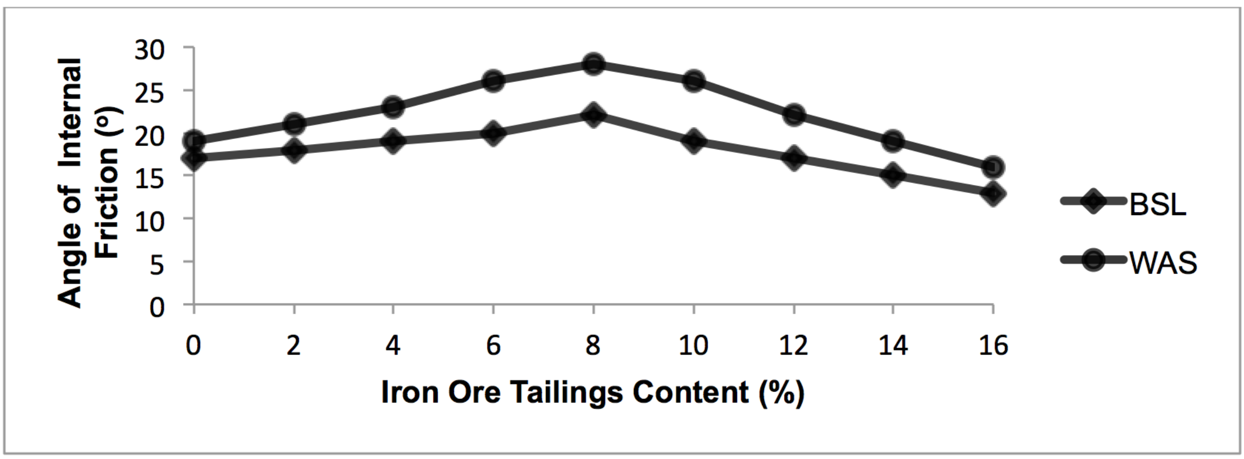

Figure 9 Variation of the angle of internal friction of lateritic soil with iron ore tailings content (IOT)

The test result of angle internal friction of IOT treated lateritic soils when compacted with BSL and WAS energies are depicted in Figure 9. Generally, the angle of internal friction increased with higher IOT content. For BSL compaction, the angle of internal friction increased from 17° for the natural lateritic soil sample to a peak value of 22° at 8% IOT content and thereafter decreased with higher IOT content to 13° at 16% IOT content. For WAS compaction, it increased from 19º for the natural lateritic soil sample to a peak value of 28° at 8% IOT content and thereafter decreased with higher IOT content to 16° at 16 % IOT content. A similar result was reported by Grytan et al. [33] that improvement of the angle of internal friction (φ) implies that the silica content in IOT act as a binder that agglomerates the particles into a larger one and the soil changes from clay to silt.

An analysis of` variance (ANOVA) of shear strength parameters test results (see Table 3) shows that the effect of IOT on lateritic soil was statistically significant.

Table 3 One-way Analysis of Variance for Shear strength parameters of Lateritic Soil-Iron Ore Tailings Mixtures

Property		Sources of Variation	Degree of Freedom	FCAL	p-value	FCRIT	Remark
	Cohesion	IOT	1	66.23	4.44607	4.49	$F_{CAL}>F_{CRIT}$, Significant effect
BSL	The angle of internal friction	IOT	1	23.11	0.000192	4.49	$F_{CAL}>F_{CRIT}$, Significant effect
WAS	Cohesion	IOT	1	287.11	1.21 E-11	4.49	$F_{CAL}>F_{CRIT}$, Significant effect
	The angle of internal friction	IOT	1	40.06	1 E- 05	4.49	$F_{CAL}>F_{CRIT}$, Significant effect

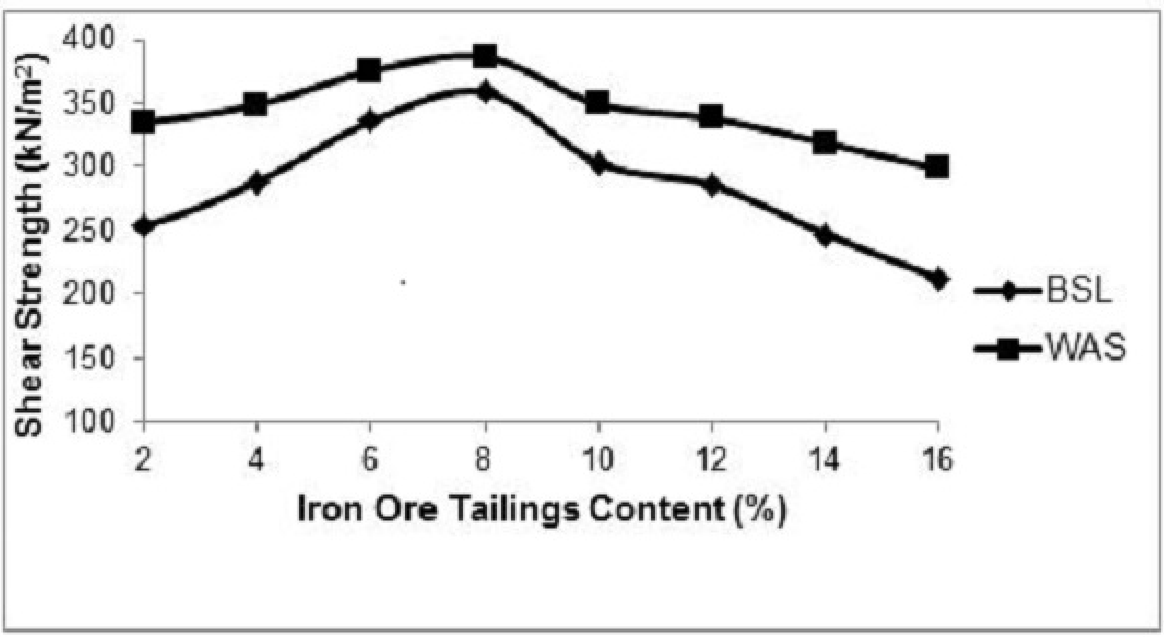

Figure 10 Variation of shear strength of lateritic soil with iron ore tailings content BSL compaction

Shear Strength

The variation of shear strength with IOT content for British Standard Light (BSL) and West Africa Standard (WAS) Compaction is shown in Figure 10. Generally, shear strength increased with increase in admixture content. For BSL compaction, shear strength of the natural soil increased from 239.12 kN/m^2 to peak value of 358.62 kN/m^2 at 8% IOT content thereafter decreases with higher IOT content. However, for West Africa Standard (WAS) energy level, an increase in shear strength was recorded for the natural soil from 326.73kN/m^2 to peak value of 386.02 kN/m^2 at 8% IOT content. A similar trend was reported by [34] where 2% maximum tire rubber fibre by dry weight of soil sample was used to improve the shear strength of the soil. An analysis of variance (ANOVA) of shear strength test results (see Table 4) shows that the effect of IOT on lateritic soil was statistically significant.

Table 4 One-way analysis of variance for shear strength of lateritic soil - IOT

Property	Sources of Variation	Degree of Freedom	FCAL	p-value	FCRIT	Remark
BSL	IOT	1	2.94E 2	1.01E11	4.49	F_{CAL}>$F_{CRIT,}$ Significant effect
WAS	IOT	1	1305.49	9.12E17	4.49	F_{CAL}>$F_{CRIT,}$ Significant effect

CONCLUSION

Based on this study, the following conclusions can be drawn.

i. The lateritic soil used was classified as A-7-6 (11) and CL according to the American Association of State Highways and Transportation Officials (AASHTO) and Unified Soil Classification System (USCS) respectively.
ii. The lateritic soil is of medium plasticity with about 22.1% of the soil particles passing through the BS. No 200 sieve.
iii. The shear strength parameters, cohesion decreased with increase in IOT content to a minimum value at 8% IOT, and the angle of internal friction increased with a higher dosage of IOT to a peak value at 8% IOT content, which showed an improvement when the shear strength parameters of lateritic soil – IOT mixture was evaluated.
iv. The shear strength increases with an increase in IOT content for the two compactive efforts considered, British Standard Light (BSL) and West Africa Standard (WAS).
v. Shear strength of British Standard light (BSL) and WAS compaction increased to the peak value of 358.62 kN/m^2 and 386.02 kN/m^2 respectively at 8% IOT content
vi. The laboratory result was subjected to statistical analysis; using analysis of variance (ANOVA) showed that IOT has a significant effect on lateritic soil as $F_{CAL} > F_{CRIT}$.
vii. An optimal blend of 8% IOT improved the shear strength of the soil and can be used for geotechnical engineering applications such as roads and embankments.

REFERENCES

[1] B.C. Punmia, J. Ashok & K.J. Arun, *Soil Mechanic and Foundations*, 16th Edition, Laxium Publications (P) Ltd, 2005.

[2] R.F. Craig, *Craig's Soil Mechanics*, London: Spon Press. 2004.

[3] S.A. Ngah & H.O. Nwankwoala, "Evaluation of Sub-Soil Geotechnical Properties for Shallow Foundation Design in Onne, Rivers State, Nigeria", *International Journal of Engineering and Sciences*, 2, 11, pp. 8-16, 2013.

[4] A.E. Annor, P.I. Olasehinde & P.C. Pal, "Basement Fracture Patterns in The Control of Water Channels – An Example from Central Nigeria", Paper presented at the 23rd Annual Conference of the Nigerian Mining and Geosciences Society, Benin, p.9, 1987.

[5] A.A. Amadi, A.O. Eberemu & K.J. Osinubi, "Strength consideration in the use of lateritic soil stabilized with fly ash as liners and covers in waste landfills", In *State-of-the Art and Practice in Geotechnical Engineering*, R.D. Hryciw, A.A-Zekkos & N.Yesiller, ASCE Geotechnical Special Publication (GSP), 225, pp. 3835-3844. 2012.

[6] P.O. Youdeowei & H.O. Nwankwoala, "Suitability of soils as bearing media at a freshwater swamp terrain in the Niger Delta", *Journal of Geology and Mining Research*, 5, 3, pp.58 –64, 2013.

[7] A. A Amadi & A. O. Eberemu, "Characterization of geotechnical properties of lateritic soil bentonite mixtures relevant to their use as barrier in engineered waste landfills", *Nigerian Journal of Technology*, 32, 1, pp.93-100, 2013.

[8] S.A. Ola, "Need for estimated cement requirement for stabilizing lateritic soil", *Journal of Transport Division, ASCE*, 17, 8, pp.379-388, 1974.

[9] M.D. Gidigasu, *Laterite Soil Engineering: Pedogenesis And Engineering Principles*, Amsterdam: Elsevier Scientific Publication Company, 1976.

[10] E.H. Seyed, K.A. Mohammad & M. Amir, "Evaluation of shear strength parameters of smended loess through using common admixtures in Gorgon", *International Scholarly and Scientific Research & Innovation*, 6, 12, pp. 1055-1058, 2012. Doi.10.5281/zenodo.1330539.

[11] K.J. Osinubi, "Influence of compactive efforts and compaction delay on lime-treated soil", *Journal of Transportation Engineering*, 124,2, pp.149-155, 1998.

[12] S.A. Ola, "Stabilization of Nigeria laterite soils with cement, bitumen and lime", *Proceedings of 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering,* pp.145-152, 1975.

[13] K.J. Osinubi, A.A. Amadi & A.O. Eberemu, "Shrinkage characteristics of compacted laterite soil-fly ash mixtures", *NSE Technical Transaction*, 41,1, pp. 36-48, 2006.

[14] K.J. Osinubi & A.T.Stephen, "Influence of compactive efforts on bagasse ash treated black cotton soil", *Nigerian Journal of Soil and Environment Research*, 7, pp. 92-101, 2007.

[15] A.B. Salahudeen, O.A. Eberemu & K.J. Osinubi, "Assessment of cement kiln dust-treated expansive soil for the construction of flexible pavements", *Geotechnical and Geological Engineering*, Springer, 32, 3, pp.1-10, 2014. Doi.10.1007/s10706-014-9769-0

[16] K. Ishola, "Modification of lateritic soil with iron ore tailing", Unpublished M.Sc Thesis Civil Engineering Department, Ahmadu Bello University Zaria, 2014.

[17] K.Ishola, O.A. Olawuyi, A.A. Bello & P. Yohanna, "Effect of plantain peel ash on the strength properties of tropical red soil", *Nigerian Research Journal of Engineering and Environmental Sciences*, 4,1, pp. 447- 459, 2019.

[18] J. Guo, W. Jianhua & Y. Guohua, "Current situation and comprehensive utilization of iron ore tailings resources in our country", *Modern Mining*, pp 23-25, (in Chinese), 2009.

[19] Z. Zhao & Z. Zhenwu, "Test for making pavement layer and binder with iron tailings", *Fujian Building Materials*. pp. 26-28. 2010.

[20] L. Yongguang & W. Xiaolei, "Development of comprehensive utilization of iron tailings as resource", *Journal of Modern Mining*, pp. 28-30, (in Chinese), 2010.

[21] L.M. Amaratunga & D.N. Yaschyshyn, "Development of a high modulus paste fill using fine gold mill tailings", *Geotechnical and Geological Engineering*. pp. 205-219, 1997.

[22] F.A. Akintola, "Geology and geomorphology", In *Nigeria in Maps*, R.M. Barbour (ed), London: Hodder & Stoughton, 1982.

[23] O. Areola, "Soils", In *Nigeria in Maps*, R.M. Barbour (ed), London: Hodder & Stoughton, 1982.

[24] AASHTO, "Standard Specifications for Transport Materials and Methods of Sampling and Testing", *American Association of State Highway and Transport Officials* (AASHTO), Washington, D.C, 1986.

[25] ASTM, "Annual book of ASTM standards, ASTM, Philadelphia, BRRI/Lyon Associates. Laterites and lateritic soils and other problem soils of Africa", *An Engineering Study for USAID*. AID/csd-2164, Baltimore, Md,1971, 4,8, 1992.

[26] BS 1377, "Methods of testing soil for civil engineering purposes", British Standards Institute, London. 1990.

[27] BS, "Methods of testing for stabilized soils", British Standards Institute, London, 1924.

[28] ASTM C618-78, "Specification for fly ash and raw or calcinated natural pozzolanas for use as a mineral admixture in Portland cement concrete", *American Society for Testing and Materials*, Philadelphia. 1978.

[29] Nigerian General Specifications, *Roads and bridges,* Abuja, Nigeria: Federal Ministry of Works,1997.

[30] K.J. Osinubi, "Evaluation of admixture stabilization of Nigeria black cotton soil", *Nigeria Society Engineering Tech. Trans*. 34, 3, pp.88-96, 1999.

[31] G. Lees, M.P. Abdelkader & S.K. Hamdani, "Effect of the clay fraction on some mechanical properties of lime-soil mixtures", *Journal First Highway Engineering*, 29, 11 pp. 2-9, 1982.

[32] D.O.A. Osula, "Lime modification of problem laterite", *Journal of Engineering Geology* 30, pp. 141-149, 1991.

[33] S. Grytan, M.D. Rafiqul, A. Muhammed & M.D. Rokonuzzaman, "Interpretation of rice husk ash on geotechnical properties of cohesive soil", *Global Journal of Researches in Engineering*, 11, 7, 2012.

[34] S.A. Naeini & S.M. Sadjadi, "Effect of waste polymer materials on shear strength of unsaturated clays", *Electronic Journal of Geotechnical Engineering*, 13, pp.1-12, 2008.