Experimental and Statistical Study on Black Cotton Soil Modified with Cement–Iron Ore Tailings

1Paul Yohanna, 2Ianna M. Kanyi, 3Roland K. Etim, 4,6Oshioname A. Eberemu, and 5Kolawole J. Osinubi

1Department of Civil Engineering, University of Jos, Jos, Nigeria
2Department of Civil Engineering, University of Agriculture, Makurdi, Nigeria
3Department of Civil Engineering, Akwa Ibom State University, Ikt Akpaden, Nigeria
4Africa Centre of Excellence in New Pedagogies in Engineering Education, Ahmadu Bello University, Zaria, Nigeria
5Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria

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Abstract- The investigation focused on the response of black cotton soil (BCS) treated with mixtures of iron ore tailings (IOT) and cement and to varying compaction effort (CE). Preliminary tests showed that the untreated soil is A-7-6 (22) on the basis of AASHTO protocols of classification while the USCS (Unified Soil Classification System) guidelines placed the soil in CH group. Laboratory tests carried out included cation exchange capacity, CEC, Specific gravity (Gs) and compaction test. Three compaction energy levels (i.e., British Standard heavy (BSH), West African Standard (WAS) and British Standard light (BSL)) were adopted for the compaction test. Test results showed that CEC decreased; Gs and MDD increased while OMC also decreased for all cement contents considered when admixed with the different IOT contents up to 10 % IOT by the soil dry weight. MDD values of 1.58, 1.59, 1.62, 1.64 and 1.66 Mg/m³ were noted for 1% cement and 0, 2, 4, 6, 8 and 10% IOT content compacted with BSL energy. Also, OMC values of 21.2, 20.8, 20.5, 20.3 and 20.2% were noted for 1% cement and 0, 2, 4, 6, 8 and 10% IOT content compacted with BSL energy. Same trend was noted for higher cement concentrations and compactive efforts. Regression models for MDD and OMC, considered as dependent variables while C (cemnet content), CE, IOT, Gs and PF (percentage of fine) as independent variables were developed using software (Mini-tab R15). The result of regression analysis shows that the dependent variables greatly influence the dependent variables. ANOVA (Analysis of variance) was use to establish the levels of contributions of cement and IOT to the improvements recorded. Therefore, black cotton soil optimally treated with 4% cement 10% IOT blend and compacted with BSH energy is recommended for soil remediation or geotechnical engineering applications.

Keywords- Compaction effort, iron ore tailings, black cotton soil (BCS), Analysis of Variance, regression analysis

1 INTRODUCTION

Environmental degradation triggered by industrial and agricultural waste has caused serious concern in pollution studies due to problems associated with the disposal of such wastes (Mangalpady, 2012). Wastes generated worldwide continued to increase apparently due to increase in global human population as well as increased industrial and socio-economic activities. One attractive and efficient way to diminish the effect of waste to the surroundings is to put in place a proper waste disposal system. Mining and mineral exploitation has profound benefits on society and the economy through income generation; however, it also generates huge overburden (waste) materials such as silt, mine tailings among others that may compromise the serenity of the environment. It has been shown through research that most industrial, agricultural and domestic wastes could be used in addressing some geotechnical problems (Ajay and Suneeet, 2016; Sharma et al., 2017; Etim et al., 2017; Rajbeer et al., 2018; Kanyi et al., 2019; Salahudeen et al., 2014; 2019; Ishola et al., 2019; Annafi et al., 2020; Ibrahim et al., 2020; Sae’ed and Augustine, 2020).

Therefore, redeploying these wastes to other uses is helpful in terms of resources conservation, improved environment and also for sustained development (Mangalpady, 2012; Osinubi et al., 2015). With the ever increasing quest for cost-saving and safe engineering in modern technology, most materials for construction in their natural state may not meet up with all the minimum requirements provided for in the standard codes, thus necessitating the improvement of such materials to meet up with the desired intent. This is why conscious efforts are being channelled towards conversion of industrial materials and “bio-wastes” to engineering products and materials (Collins and Ciesielski, 1993). To achieve this, industrial manufactured additives (bitumen, lime, cement) and “industrial waste” such as iron ore tailings (IOT) had at various times been used to modify soils including black cotton soils that are deemed unstable and unfit for engineering use in its natural state.

IOT are industrial bye-products obtained from the beneficiation process of iron ore from the mining industry. The Agbaja and Itakpe iron ore deposits have generated significant number of impurities in Nigeria. The Agbaja ore deposit is acidic olite ore which has magnetite and goethite with silica, phosphorus and alumina as impurities while the Itakpe iron ore consist of haematite with silica and magnetite being its major impurity. The Itakpe ore deposit is estimated to be about 200 million tons (Adedeji and Sale, 1984).

Black cotton soil (BCS) is known to expand, swell or shrink in excess when there is variation in amount of moisture (Ola 1983). When civil infrastructures are built with or on these soils, it experiences the shrinkage or swell property depending on the level of stress it is exposed to. It is therefore quite tasking to carry out design and construction involving the use of this soil due to its un-usual behaviour. These soils mostly found in the hot environment in the semi – arid areas of the temperate and tropical climate zone with defined alternating dry and wet seasons and where evaporation exceeds precipitation (Chen, 1988). They are largely located on sedimentary plains as a result continuous erosion of the clay content out of nearby hills. BCS can likewise be found on low level areas and depressions.

*Corresponding Author
Available researches (NBRI, 1983 and Ola, 1983) indicated that deposits of BCS found in Nigeria were formed towards the end of Quaternary and Tertiary periods during Chad formations comprising of sands of Pleistocene age as well as a sequence of lacustrine and fluviatile clay. According to Ola (1983), montmorillonite (clay mineral) predominates BCS and it represents one of the most difficult soils to work with in Africa. BCS in Nigeria is estimated to cover an area of about 104,000 km², usually with little or no amount of organic content in the soil, and its black colouration is probably due to titanium or iron (Jha and Sinha, 1993). Osinubi (1995) reported that in regions where BCSs are located, most deposits have been found to cover large expanse areas that by-passing or avoiding them is not always feasible.

The research laboratory testing programs were tailored with the aim of evaluating the effect of compaction efforts and IOT on cement modified BCS. The objective was to investigate the behavioural alterations in the relevant geotechnical characteristics of the soil at different cement and IOT contents for application as a road construction material under different compaction energies.

2 MATERIALS AND METHODS

2.1 MATERIALS

Soil: The BCS samples were sourced at a location on Longitude 11° 30’E and Latitude 10° 19’N from Gombe state. The disturbed sampling method was used to obtain soil samples at a depth of 0.5 m and placed in bags while those for natural moisture content determination were placed in plastic bags to eliminate moisture escape during transit and conveyed to the laboratory. In the laboratory, the air dried and pulverized specimens were run through a standard sieve BS No. 4 sieve (4.76 mm).

Cement: The ordinary Portland cement (OPC) was purchased from a retail shop in the open market within Zaria.

Iron Ore Tailings: The IOT was sourced at the National Ore Mining Company located at Itakpe, Kogi state, Nigeria.

2.2 METHODS

Index Properties: Natural moisture content, Atterberg limits, particle gradation curve and specific gravity tests were performed in line with British Standards (BS 1377 (1990) and BS 1924 (1990)). Soil specimens were treated with 0, 2, 4, 6, 8, and 10 % IOT and 1, 2, 3 and 4 % cement of soil dry weight.

Cation Exchange Capacity: The test was performed in line with the techniques given by ISRIC (1998). Soil specimens were treated with 0, 2, 4, 6, 8, and 10 % IOT and 1, 2, 3 and 4 % cement of soil dry weight prior testing.

Compaction: Tests involving compaction were carried out in line with BS 1377 (1990) and BS 1924 (1990) procedures to compute the desired parameters. Three compaction energies were used which include; British Standard heavy (BSH) British Standard light (BSL), and West African Standard (WAS) energy levels.

Statistical Analysis: Laboratory tests on grading and compaction characteristics and the factors connected with grading and compaction characteristics were obtained via laboratory tests. Factors measured include; Maximum dry density (MDD) and Optimum moisture content (OMC) as dependent factors and Cement content (C), Iron ore tailings content (IOT), Sand content (Sa), Percentage fine (PF) and Specific gravity (Gs) as independent factors while Compactive effort (CE) is assumed to be a deterministic parameter with index values of –1, 0 and 1 assigned arbitrary for BSL, WAS and BSH compaction efforts respectively. The regression studies were done using Mini-tab R15 software. Analysis of variance was achieved with Microsoft Excel 2007.

3 RESULTS AND DISCUSSION

3.1. INDEX PROPERTIES

Characteristics of the un-treated soil sample (BCS) revealed through visual inspection a greyish black colour and laboratory tests values of 56%, 25% and 31% representing LL, PL and PI respectively. Further preliminary tests showed that it is an A-7-6 (22) soil on the basis of AASHTO protocols of classifying soil (AASHTO, 1986) while using the USCS (Unified Soil Classification System) guidelines (ASTM, 1992), the un-treated soil was found to be CH. The soil was also found to be of low plasticity and fell short of minimum standard recommendation for a lot of civil infrastructure most notably highway construction (Butcher and Sailie, 1984).

The summarized index tests result is as presented in Table 1. More on the index properties have been discussed extensively in previous researches (Yohanna, et. al., 2014). The natural soil particle gradation curve is also as presented in Fig 1. Grading properties of the natural soils shows 2.8% gravel, 23% sand and 74.2% fine (comprising of silt and clay). It is clear that more than 70% of the soil comprises of silt and clay particles which are not good for pavement applications as proposed by Nigerian General Specifications (1997) and hence the need for the soil improvement.

| Table 1. Properties of the Natural Soil |
|-----------------------------------------|
| percentage passing 0.075mm sieve         | 74.2 |
| Natural moisture content %              | 19.5 |
| Liquid limit %                         | 56   |
| Plastic limit %                        | 25   |
| Plasticity index %                     | 31   |
| Cation Exchange Capacity (CEC), Cmol/Kg | 52.52|
| AASHTO classification                   | A-7-6(22) |
| USCS                                    | CH   |
| Maximum dry density Mg/m³              |      |
| BSL                                     | 1.56 |
| WAS                                     | 1.64 |
| BSH                                     | 1.68 |
| Optimum moisture content %             |      |
| BSL                                     | 23.5 |
| WAS                                     | 20   |
| BSH                                     | 19.3 |

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Table 2. Oxide compositions of cement and iron ore tailings

| Oxide                  | *Cement (%) | **Iron ore tailings (%) |
|------------------------|-------------|-------------------------|
| Silica (SiO₂)          | 20.0        | 45.64                   |
| Iron Oxide (Fe₂O₃)     | 3.0         | 47.7                    |
| Alumina (Al₂O₃)        | 6.0         | 3.36                    |
| Lime (CaO)             | 63.0        | 0.607                   |
| Magnesium Oxide (MgO) | -           | 0.393                   |
| Manganese Oxide (MnO)  | -           | 0.067                   |
| Nickel Oxide (NiO₂)    | -           | -                       |
| Tin Oxide (TiO₂)       | -           | -                       |
| Alkali (Na₂O)          | 1.0         | 0.405                   |
| Alkali (K₂O)           | -           | 0.607                   |
| Sulphur Oxide (SO₃)    | 2.0         | -                       |
| Vanadium Oxide (V₂O₅)  | -           | -                       |
| (Loss on Ignition)     | 2.0         | -                       |

*Czernin (1962), **Osinubi et al., (2015).

3.3. SPECIFIC GRAVITY

The specific gravity ($G_s$) of BCS-cement blended with different amount of IOT is presented in Fig 3. The $G_s$ values show the tendency to increase when more quantity of IOT was used. The $G_s$ value of un-treated soil increased from 2.46 to a highest value of 2.56 at 0% cement and 10% IOT blend. The observed behaviour could be tied to the high $G_s$ value of IOT (3.29) relative to soil with a low $G_s$ value of 2.46. Similar increasing tendency after treatment was also reported by Amadi, (2010).

3.4. COMPACTION CHARACTERISTICS

3.4.1. Maximum Dry Density

The alteration in MDD values of BCS - cement blended with varying amount of IOT is as presented in Fig 4 for BSH, WAS and BSL compactions. The results indicated a hike in MDD values with more cement and IOT contents for the three energy levels considered. MDD values also increased with an increase in compaction effort. Trends akin to the above were also noted by Phanikumar et al. (2004) Oriola and Moses (2010) and Kumar and Puri (2013). The observed increments in MDD values after treatment may be owed to IOT and cement taking up empty spaces inside the blended soil in addition to CEC reaction resulting to the agglomeration and flocculation of the clay particles. This is in the affirmative with the reported findings by Osinubi, (1999; 2000), Moses (2008), Jadhao and Nagarnaik (2008), Amadi (2010), Oriola and Moses (2011), Osinubi and Oyelakin (2012) and also Anafi et al., (2020). The noted increment in MDD values could also be tied to the high $G_s$ of the additives replacing soil particles with lower $G_s$. 
3.4.2. Optimum Moisture Content

The change in optimum moisture content (OMC) of BCS - cement mixture with IOT for the compaction energies considered is presented in Fig 5. It could be deduced from the plots that the OMC values decreased when cement and IOT contents were increased for all compactive efforts considered in the study. OMC values also decreased with an increase in compaction effort. This behaviour may be traced to self – desiccation of the resulting soil – additives blend, the process which used up all available moisture culminating in low hydration. When the movement of water is no longer permitted into or out of the resulting soil-IOT-cement matrix, the available moisture is used up during the hydration process till very small amount is left to moisten the solid surfaces thus ensuring low proportionate humidity in the paste (Osinubi, 2001; Moses et al., 2012). The consequence of the above process might likely have some effect on the reaction of cement-IOT treated BCS. Some reported findings that conform to this were those of Osinubi and Stephen (2007), Moses (2008), Kanyi et. al. (2017; 2019); Salahudeen and Sadeq (2019). The decrease in OMC is attributed to the added IOT content which is classified as silty sand to the parent material. This is in conformity with earlier research by Kumar and Puri (2013).

Generally, the correlation coefficient values ($R^2$) of 92.0% for MDD and 86.1% for OMC shows that the independent parameters are more correlated to the MDD than OMC. The regression equations are:

\[
\begin{align*}
MDD &= 0.735 + 0.00071C + 0.00857IOT + 0.00034s_S + 0.0001PF + 0.35G_s + 0.0939CE \\
R^2 &= 92.0 \\
OMC &= 40.9 + 0.276C - 0.283IOT - 0.0055s_S + 0.076PF - 10.7G_s - 0.62CE \\
R^2 &= 86.1 
\end{align*}
\]

where MDD = Maximum dry density (Mg/m$^3$), C = Cement content (%), IOT = Iron ore tailing content (%), $s_S$ = Sand (%), $G_s$ = Specific gravity, PF = Percentage fine (%), CE = Compactive effort and OMC = Optimum moisture content (%).

### 3.6. Two-Way Analysis of Variance for Black Cotton Soil – Cement – IOT Mixtures.

The two-way analysis of variance (ANOVA) test performed on compaction behaviours are given in Table 2. The analysis shows that the IOT ($F_{CAL} = 12.15174 > F_{CRIT} = 1.662901$) and Compactive effort ($F_{CAL} = 585.9843 > F_{CRIT} = 3.15932$) significantly affected MDD values of the modified soil. However, the effect of CE on the MDD of BCS was much more significant. For OMC the analysis shows that the IOT ($F_{CAL} = 11.63807 > F_{CRIT} = 1.662901$) and Compactive effort ($F_{CAL} = 361.7148 > F_{CRIT} = 3.15932$) significantly affected OMC values of the modified soil. However, the effect of CE on the OMC of BCS was much more significant.

![Fig. 5: Change in OMC of BCS- cement mixtures with IOT content](image)

| Property | Source of Variation | $F_{CAL}$ | $p$-value | $F_{CRIT}$ | Remark |
|----------|---------------------|-----------|-----------|-----------|---------|
| MDD      | IOT                 | 12.15     | 1.41E-15  | 1.66      | $F_{CAL} > F_{CRIT}$, SS |
|          | CE                  | 585.98    | 3.41E-39  | 3.16      | $F_{CAL} > F_{CRIT}$, SS |
| OMC      | IOT                 | 11.64     | 3.8E-15   | 1.66      | $F_{CAL} > F_{CRIT}$, SS |
|          | CE                  | 361.71    | 1.76E-33  | 3.16      | $F_{CAL} > F_{CRIT}$, SS |
4 CONCLUSION
Based on the results of the study the following conclusions were drawn. The natural soil is fine-grained soils and classified as A-7-6 (22) according to AASHTO classification protocols and CH using the Unified Soil Classification System, USCS guidelines. CEC decreased; Gs and MDD increased while OMC decreased for all cement contents considered when admixed with up to 10% IOT content by dry weight of soil. Regression analysis on the test results shows that the correlation coefficient values (R²) of 92.0% for MDD and 86.1% for OMC shows that the independent parameters considered are more correlated to the MDD than OMC.

The results of the laboratory tests and statistical analysis showed improvement in the geotechnical properties of the soil with cement-IOT blend. Therefore, an optimal blend of 4% cement and 10% IOT treated black cotton soil compacted with BSH energy is recommended for soil remediation or geotechnical engineering applications.

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