AN EXPERIMENTAL STUDY ON COMPACTION BEHAVIOR OF LATERITIC SOILS TREATED WITH QUARRY DUST BASED GEOPOLYMER CEMENT

Kennedy Chibuzor Onyelowe[1*], Duc Bui Van[2], Mohammed Oludare Idrees[3], Michael E. Onyia[4], Lam Dao-Phuc[5], Favour Deborah A. Onyelowe[6], Talal Amhadi[7], Felix Sosa[8], Adrian Eberemu[9], A. Bunyamin Salahudeen[10], Kolawole Osinubi[9], Francis Orji[11], Clifford Igboayaka[12], Chidozie Ikpa[13], Manh Nguyen Van[2], Benjamin Ugorji[14], Kizito Ibe[14], Manh Nguyen Xuan[2]

[1]Senior Lecturer, Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, P.M.B. 7267, Umuahia 440109, Abia State, Nigeria; Principal Researcher, Research Group of Geotechnical Engineering, Construction Materials and Sustainability, Hanoi University of Mining and Geology, Hanoi, Vietnam; Adjunct Senior Lecturer, Department of Civil Engineering, Faculty of Engineering, Alex Ekwueme Federal University, Ndufu-Alike Ikwo, Ebonyi State, Nigeria & Visiting Scholar (Reader), Department of Mechanical and Civil Engineering, Faculty of Engineering, Kampala International University Western Campus, Ishaka, Uganda
[2]Faculty of Civil Engineering, and Research Group of Geotechnical Engineering, Construction Materials and Sustainability, Hanoi University of Mining and Geology, Hanoi, Vietnam.
[3]Senior Research Fellow, Geospatial Information Science Research Lab, Department of Civil Engineering, Faculty of Engineering, University Putra Malaysia, Serdang, Malaysia
[4]Head/Senior Lecturer, Department of Civil Engineering, Faculty of Engineering, University of Nigeria, Nsukka, Nigeria
[5]Faculty of Civil Engineering, University of Transportation Technology, Hanoi, Vietnam
[6]Department of Biotechnology, Ebonyi State University, Abakaliki, Ebonyi State, Nigeria
[7]Doctoral Research Fellow, Department of Construction and Civil Engineering, Ecole de Technologie Superieure (ETS), University of Quebec, Montreal, Canada
[8]Doctoral Research Fellow, Department of Civil Engineering, National Autonomous University of Mexico, Mexico City
[9]Professor, Department of Civil Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria
[10]Department of Civil Engineering, Faculty of Engineering, University of Jos, Nigeria
[11]Department of Mechanical Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria
[12]Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, P.M.B. 7267, Umuahia 440109, Abia State, Nigeria
[13]Lab Technologist, Department of Civil Engineering, Faculty of Engineering, Alex Ekwueme Federal University, Ndufu-Alike Ikwo, Ebonyi State, Nigeria
[14]Graduate Assistants, Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, P.M.B. 7267, Umuahia 440109, Abia State, Nigeria

konyelowe@mouau.edu.ng, kennedy.onyelowe@funai.edu.ng, kennedychibuzor@kiu.ac.ug

ABSTRACT

Due to the scarcity of well-graded gravel materials, lateritic soils are widely used for road construction in tropic areas. However, lateritic soils often do not meet the strict requirement for subgrade and need to be improved to be used as construction material. Among several approaches used to enhance the engineering properties of lateritic soils, the use of industrial waste materials, such as fly ash, granulated blast furnace slag, is of particular interest to the construction industry as a potential replacement material for Portland cement in soil stabilization. Meanwhile, some effort has been made to study the use of quarry dust in stabilizing lateritic soils. The present work aims at assessing the compaction characteristics of three different types of lateritic soils, treated with quarry dust based geopolymer cement. A systematic study by varying the proportion of geopolymer cement was carried out. Test results show that the soil dry density substantially increased while the corresponding optimal moisture content decreased with the amount of geopolymer cement under varying compactive effort.

Keywords: Rammer Blows; Lateritic Soils; Quarry Dust; Geopolymer cement; Compaction Characteristics; Compaction Effort

INTRODUCTION

The disposal of quarry dust (QD) as a solid waste from quarrying operations into the landfills has been a challenging practice in the developing world. Quarry dust is an amorphous waste product of rock quarry operation of highly aluminosilicate content (Fedrigo et al., 2017). This inorganic composition gives quarry dust the highly pozzolanic proper-

---

**Corresponding author*

ties (Fedrigo et al., 2017; K.C.Onyelowe *et al.*, 2019a, 2019b, 2019c & 2019d). Geopolymers, on the same hand, are produced from amorphous materials of highly aluminosilicate content though with activator compounds of sodium or potassium, which enhances the attainment of a steady state with the stoichiometric release of Si and Al in the geopolymer synthesis chain, leading to polycondensation (Nikolov et al., 2017; Salahudeen *et al*., 2014; K. C. Onyelowe *et al.*, 2020a; 2020b; 2020c). The primary solid waste materials in this procedure are fly ash, ground granulated blast furnace slag, and activators like Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3). According to research results on the synthesis of geopolymer cements, these materials are mixed in the proportion of 44% by weight of fly ash, 44% by weight proportion of ground granulated blast furnace slag and 4.8% or less by weight proportion of activators (NaOH + Na_2SiO_3) in order to achieve an eco-friendly or user friendly geopolymer (Abdel-Gawwad & Abo-El-Enein, 2016; Akbari, Mensah-Biney, & Simms, 2015; Davidovits, 2013; Hamidi, Man, & Azizli, 2016; Mubayi, Chatterji, Rai, & Watal, 2012; Nikolov, Rostovsky, & Nugteren, 2017; Škvára, Jílek, & Kopecký, 2005; Srinivasan & Sivakumar, 2013; K.C.Onyelowe *et al.*, 2019a, 2019b, 2019c & 2019d). From the aforementioned studies, it can be deduced that quarry dust can replace in full or partially fly ash or ground granulated blast furnace slag because of its aluminosilicate content, which is the most important property in the synthesis and application of geopolymer cements or binders in geomaterials as hydraulically bond materials. Yet, because the ground granulated blast furnace plays a very important role in at room temperature setting of the Geopolymer cements, it cannot be replaced with another material of very different properties. It produces the sufficient calcium cations (Ca^{2+}) needed for hardening and strength gain at room temperature (Davidovits, 2013; Osinubi *et al*., 2017; Osinubi & Eberemu, 2008; Osinubi & Eberemu, 2019) and for the purpose of this research exercise, quarry dust was used as a 22% by weight replacement of fly ash. On the other hand, alkaline silicates are better activators than alkaline hydroxyls because the former (alkaline silicates) produces Geopolymer cements of higher compressive strength at 28 days. The later (alkaline hydroxyls) produces Geopolymer cements with lower compressive strength with higher tendency of shrinkage and higher relative volume of the pores observed in Geopolymer cements based on NaOH. It is important to note that both NaOH and Na_2SiO_3 are adapted in the ratio of 1.6% to 3.2% by weight to ensure a higher release of silicates, which will improve the physico-mechanical properties of the metallurgical slag (Akbari, Mensah-Biney, & Simms, 2015; Damilola, 2013; Ghosh, Kumar, & Biswas, 2016; Zain, Abdullah, Hussin, Ariffin, &Bayuaji, 2017). Care must be taken to achieve NaOH molar concentration of 12 M, from which the 1.6% by weight of NaOH is obtained and used as an activator material (Akbari, Mensah-Biney, & Simms, 2015; Srinivasan & Sivakumar, 2013). Geopolymers are products of geopolymerization reaction which have been proven, unlike Portland cements, to have high resistance to acids, high temperature beyond 600°C, corrosive action of salts, frost, etc. (Hamidi, Man, & Azizli, 2016; Eberemu *et al.*, 2014; K. J. Osinubi *et al*., 2012). Geopolymer cements, binders and concretes have found wide applications in the infrastructures development industry and exhibits great use in solid waste management, construction repair as geopolymer injection, toxic metal immobilization and coatings (Bromley & Hadfield, 2017; Bui Van, Onyelowe, & Van Nguyen, 2018; Bykkam, Ahmadipour, Narisngam, Kalagadda, & Chidurala, 2015; Hamidi, Man, &Azizli, 2016; Raki, Beaudoin, Alizadeh, Makar, & Sato, 2010; Van Duc & Kennedy, 2018; Xiao, Cai, Wang, Lai, & Chu, 2005; Eberemu *et al*., 2012; Eberemu, 2013; K.J. Osinubi & A. O. Eberemu, 2013). The application of blended quarry dust base geopolymer for the treatment of compacted soils was investigated in the present work. However, the specific objectives were; (i) to study the effect of Geopolymer cements addition on weak expansive cemented and uncemented lateritic soils, and (ii) to also study the effect of varying compaction efforts on the compaction characteristics of treated soils.

MATERIALS PREPARATION AND EXPERIMENTAL METHODS

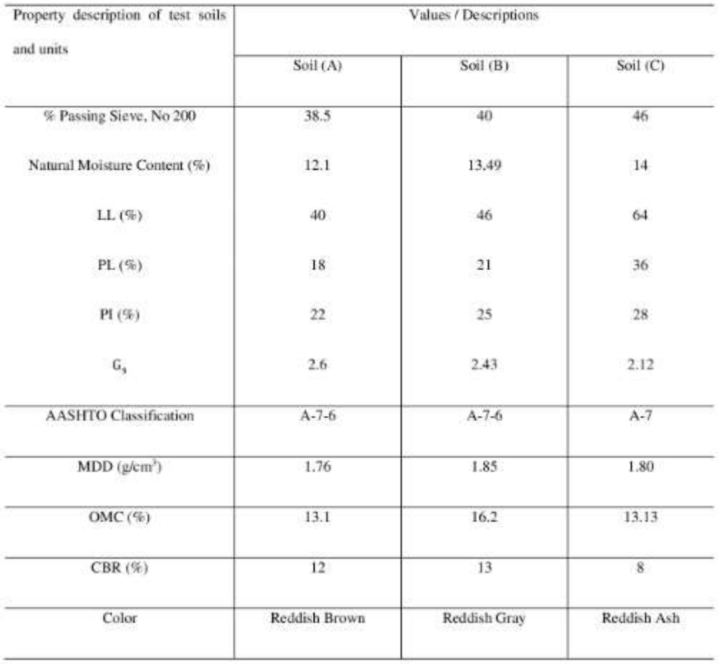
Materials Collection and Preparation

The test soil specimens used in this study were obtained from three different borrow pit locations, with coordinates of 5°29'16"North and 7°28'58" East (Olokoro area), 5°31'0" North and 7°26'0" East (Ohia area), and 5°27'0" North and 7°31'60" East (Amaba area), respectively. Soil samples were collected by using a pick and shovel. The disturbed soil samples were then tapped to eliminate lumps, sun dried for 3 days. Basic properties, grain size distribution and oxides composition of the three studied soil specimens are shown in Tables 1, 2 and Figure 2, respectively.

Quarry dust used in this study was generated throughout crushed-rock process. After being taken from a quarry site in Ebonyi State, Nigeria, the collected quarry dust was sundried before being ultilized. Fly ash and ground granulated blast furnace slag samples were taken from NigerPet Structures in Uyo state and Delta Steel Company in Warri city, Nigeria, respectively. Grain size distribution and oxides composition of the quarry dust, fly ash, and ground granulated blast furnace slag are shown in the Table 2, Table 3, and Figure 2. Dangote ordinary Portland cement was also employed to make dry Geopolymer cement powder with its basic properties are summarized in the Tables 2, 3.

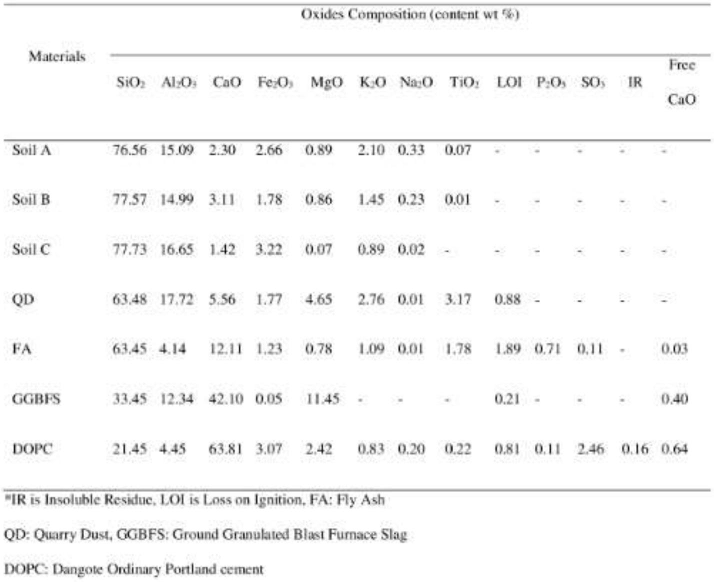
Based on the previous findings of (Abdel-Gawwad & Abo-El-Enein, 2016; Akbari, Mensah-Biney, & Simms, 2015; Davidovits, 2013; Hamidi, Man, & Azizli, 2016; Nikolov, Rostovsky, & Nugteren, 2017; Škvára, Jílek, & Kopecký, 2005; Srinivasan & Sivakumar, 2013), the quarry dust based Geopolymer cement was synthesized. In this work, aluminosilicate materials required to materialize the Geopolymer cement consist of fly ash and ground granulated blast furnace slag. The geopolymerization process of the Geopolymer cements takes place under the reactive stimulus of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) which act as activators. According to previous research, a molarity of NaOH of 12 was chosen for an eco-

TABLE 1
Basic properties of test soils



Property description of test soils and units	Values / Descriptions		
	Soil (A)	Soil (B)	Soil (C)
% Passing Sieve, No 200	38.5	40	46
Natural Moisture Content (%)	12.1	13.49	14
LL (%)	40	46	64
PL (%)	18	21	36
PI (%)	22	25	28
G_s	2.6	2.43	2.12
AASHTO Classification	A-7-6	A-7-6	A-7
MDD (g/cm³)	1.76	1.85	1.80
OMC (%)	13.1	16.2	13.13
CBR (%)	12	13	8
Color	Reddish Brown	Reddish Gray	Reddish Ash

TABLE 2
Oxides Composition of the materials used in this paper



Materials	Oxides Composition (content wt %)												
	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2	LOI	P_2O_5	SO_3	IR	Free CaO
Soil A	76.56	15.09	2.30	2.66	0.89	2.10	0.33	0.07	-	-	-	-	-
Soil B	77.57	14.99	3.11	1.78	0.86	1.45	0.23	0.01	-	-	-	-	-
Soil C	77.73	16.65	1.42	3.22	0.07	0.89	0.02	-	-	-	-	-	-
QD	63.48	17.72	5.56	1.77	4.65	2.76	0.01	3.17	0.88	-	-	-	-
FA	63.45	4.14	12.11	1.23	0.78	1.09	0.01	1.78	1.89	0.71	0.11	-	0.03
GGBFS	33.45	12.34	42.10	0.05	11.45	-	-	-	0.21	-	-	-	0.40
DOPC	21.45	4.45	63.81	3.07	2.42	0.83	0.20	0.22	0.81	0.11	2.46	0.16	0.64

*IR is Insoluble Residue, LOI is Loss on Ignition, FA: Fly Ash

QD: Quarry Dust, GGBFS: Ground Granulated Blast Furnace Slag

DOPC: Dangote Ordinary Portland cement

friendly material and better strength properties of geopolymer might be attained. Synthesis of geopolymer matrixes was carried out by mixing these above materials in a proportion of 4.8% activator, plus 22% quarry dust, plus 22% fly ash, plus 44% ground granulated blast furnace slag by weight.

Experimental Investigation on Lateritic Soils Treated with Quarry Dust-Based Geopolymer

All the three different natural lateritic soil specimens were tested to assess their basic and engineering properties. Gradation test was implemented to examine the particle size distribution of three study soils namely soil A, soil B, and soil C, respectively. The gradation test was executed in conformity with (BS 1377 - 2, 1990; NGS, 1997). The compaction tests were executed using the standard proctor test with 2016 ELE Automatic Compactor Machine according to (BS 1377 - 2, 1990; BS 1924 - 2, 1990; NGS, 1997). The California Bearing Ratio (CBR) tests were implemented with a load constant rate of 1.27 mm/min (1 mm/min to BS spec.) by using a 2015 S211 KIT CBR penetration machine according to(BS 1377 - 2, 1990; BS 1924 - 2, 1990; NGS, 1997). Consistency limits of test soil specimens were evaluated using a 2013 Casagrande apparatus in conformity with to (BS 1377 - 2, 1990; BS 1924 - 2, 1990; NGS, 1997). Specific gravity of test soils were computed by using Pycnometer method which is in accordance with to (BS 1377 - 2, 1990; BS 1924 - 2, 1990; NGS, 1997). Basic properties, compaction characteristics, and consistency limits of test soils are presented in the Table 1. According to AASHTO classification system (American Association of State & Transportation (AASHTO), 1993), soil A, soil B and soil C are characterized as A-7-6, A-7-6 and A-7 groups, respectively. Similarly, the three types of test soils were classified as poorly graded (CP) soils according to USCS. In addition, the obtained results indicate that clay content found in soil A and soil C is higher than that found in the soil B. Since plasticity index of the three test soils A, B, C were of 22, 25, and 28% which are larger than 17%, hence they were described as highly plastic and expansive soils.

Chemical compositions of the three studied soils and the test materials such as quarry dust, fly ash, ground granulated blast furnace slag, and Portland cement were determined in accordance with (BS 1377 - 2, 1990; BS 1924 - 2, 1990; NGS, 1997). Oxides compositions of the study materials are shown in the Table 2. The tested results show that the study materials exhibit pozzolanic properties and high aluminosilicate content as well.

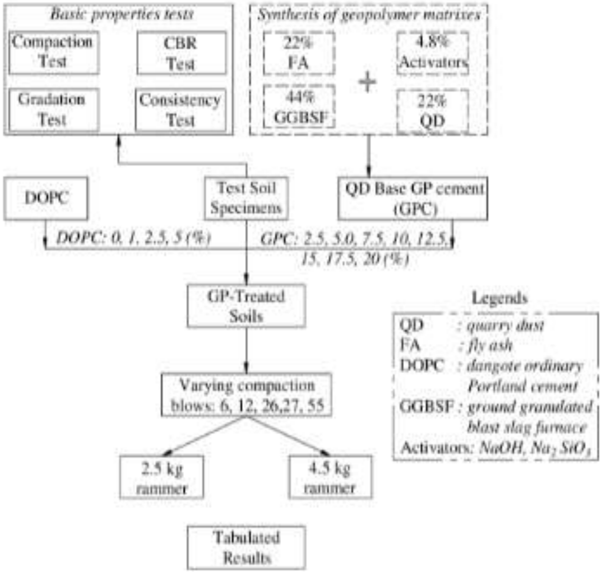


FIGURE 1
Schematic Presentation of the Experimental Program

Both standard and modified proctor compaction tests were employed to assess the compaction characteristics of treated lateritic soils. The treated soils were exerted to various number of blows of 6, 12, 26, 27, and 55, respectively. Meanwhile, two different rammers of 2.5 kg and 4.5 kg were utilized to compact the treated soils with 3 and 5 compaction layers were applied with the aim at taking various energy of compaction into account. The compaction tests were executed for both uncemented and cemented test soils in conformity with (BS 1377 - 2, 1990; BS 1924 - 2, 1990; BS 5930, 2015; NGS, 1997). Flow chart of the experimental program is shown in Figure 1.

RESULTS AND DISCUSSIONS

Effect of Varying Proportions of Quarry Dust based Geopolymer on Cemented and Uncemented Test Soil A under Varying Blows

The Geopolymer cement treated test soil A which was cemented with 5% Portland cement showed a consistent strength density gain at zero addition of Geopolymer cement under varying compaction blows and compaction efforts. The use of the modified proctor mould rammer of 4.5kg produce a higher compaction energy than the standard proctor mould rammer of 2.5kg. Again, the blows between 6 and 55 produce different density gain which increased with increased blows. Subsequently, the quarry dust based Geopolymer cement was added in the proportion of 2.5%, 5%, 7.5% to 20% in that order which equally produced significant strength gain. It was so remarkable that a control density of between 1.78 and 1.97g/cm^3 at zero Geopolymer cement produced densities in the range of 3.89 to 6.89g/cm^3 at 20% by weight addition of quarry dust based Geopolymer cement under compaction blows of between 6 and 55 as presented in

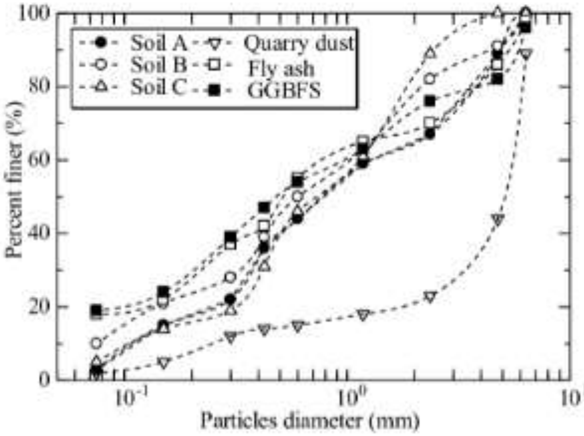
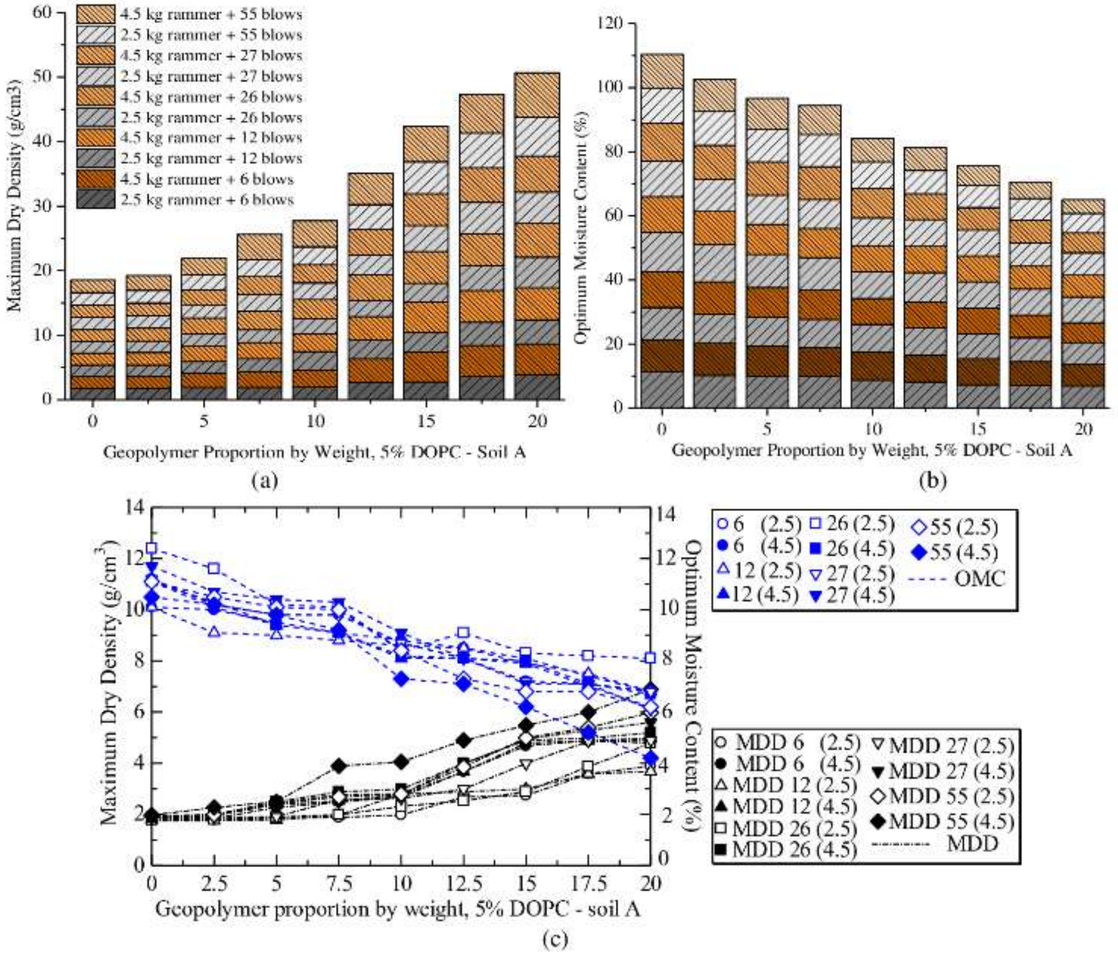


FIGURE 2
Particle size distribution of studied materials

Figure. 3. It is important to note that this behaviour may be due to the increased compaction effort produced by both rammer sizes and number of blows per layer, which enhanced the interlocking between the microstructure of the soil and in turn reduced the porosity in the treated matrix, thereby increasing densification and flocculation, consequently higher strength might be gained(Fwa, 2005; Gidigasu & Dogbey, 1980; Meegoda & Ratnaweera, 1994; Nnochiri & Ogundipe, 2016; K. Onyelowe, 2017a, 2017b; K. Onyelowe & Okafor, 2015; K. C. Onyelowe, 2017; K. C. Onyelowe & Duc, 2018; Osinubi, 2000; Osinubi, Bafyau, &Eberemu, 2009; Srinivasan & Sivakumar, 2013; Amadi & Eberemu, 2012; K. J. Osinubi *et al.*, 2012; Eberemu *et al.*, 2013; K.C.Onyelowe *et al.*, 2019a, 2019b, 2019c & 2019d). This point to the fact that higher compaction effort may encourage the use of little or no Portland cement reducing cost, and shrinkage potential.

Secondly, the increased proportions of quarry dust based Geopolymer cement may have caused a consistent strength gain in the treated matrix. This behaviour gained is because the Geopolymer cement may have filled the voids within the soil mass during the stabilization proce porosity of the treated soils. Additionally, because of its pozzolanic properties which enhanced calcinations reaction, pozzolanic reaction, and the inclusion of Na_2SiO_3 in NaOH solution, Geopolymer cement provides higher silicate concentration and gives rise to the formation of gel which likely fastened polymerization, and consequently polycondensation which led to the obvious gain in strength of the treated soils (Meegoda & Ratnaweera, 1994; Eberemu & Osinubi, 2010; Nnochiri & Ogundipe, 2016; K. Onyelowe & Okafor, 2015; K. C. Onyelowe & Duc, 2018; Srinivasan & Sivakumar, 2013). The Na_2SiO_3 acted as a nucleating site then increased with the amount of silicates released, leading to the formation of more hydration points. As the concentration of hydration materials increased, the number of contact points between hydration materials also increased, consequently forming a solid microstructure within the treated soils matrixes. As presented in



(a)

(b)

(c)

FIGURE 3

Compaction of Test Soil A at 5% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

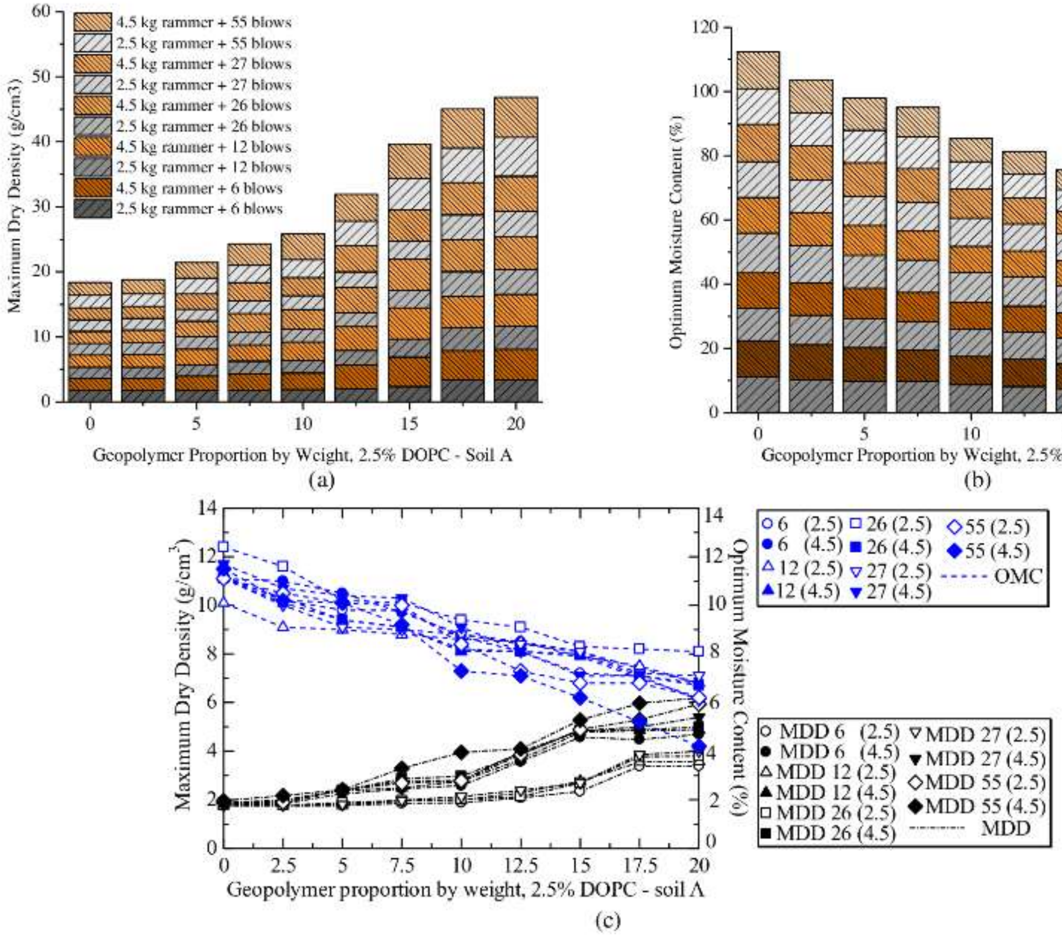


FIGURE 4

Compaction of Test Soil A at 2.5% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

Figures 4 and 5, the proportions of Portland cement were reduced to 2.5% and 1%, respectively. These percentages were used to cement the test soils at varying proportions of quarry dust based Geopolymer cement. The behaviour of the treated soils showed almost the same results, but with a very little reduced strength compared to the behaviour with 5% Portland cement cementation. At 0% Portland cement as shown in Figure 6, the treated soil A gained significant strength because it recorded between a range of 1.74 and 1.95g/cm^3 at zero Geopolymer cement (Figure 6a, c), and of 3.37 and 5.89 g/cm^3 at 20% by weight Geopolymer cement under varying compactive efforts, which were almost the range strength density gain at 5, 2.5 and 1% addition of Portland cement. The optimum moisture content (OMC) at which these densities were recorded was observed to decrease consistently too over the increased compaction blows and increased proportions of quarry dust based Geopolymer cement (Figure 6b, c). This may be due to the finely ground quarry dust based Geopolymer cement which acted as a filler material, leading to decreased porosity and then reduced moisture at which maximum densification was achieved (Abdel-Gawwad & Abo-El-Enein, 2016; Davidovits, 2013; Fwa, 2005; Meegoda & Ratnaweera, 1994; Nikolov, Rostovsky, & Nugteren, 2017; Onyelowe & Duc, 2018; Osinubi, Bafyau, & Eberemu, 2009). This behaviour shows that quarry dust based Geopolymer cement possesses the properties with which to completely replace ordinary Portland cement in the stabilization protocol, which is a positive turn as it bothers on environmental effects of cement usage in geotechnical engineering operations and civil engineering works as a whole. Previous study found that for one tonne of ordinary Portland cement produced or used, an equivalent one tonne of CO_2 emission may be released into the atmosphere, which contribute to global warming and this is an environmental global issue (Davidovits, 2013; Srinivasan & Sivakumar, 2013).

Effect of Varying Proportions of Quarry Dust Based Geopolymer on Cemented and Uncemented Test Soil B under Varying Blows

The compaction characteristics of soil B at 5% Portland cement were displayed in the Figure 7a, 7b, and 7c, respectively. The obtained results indicate an analogous behaviour

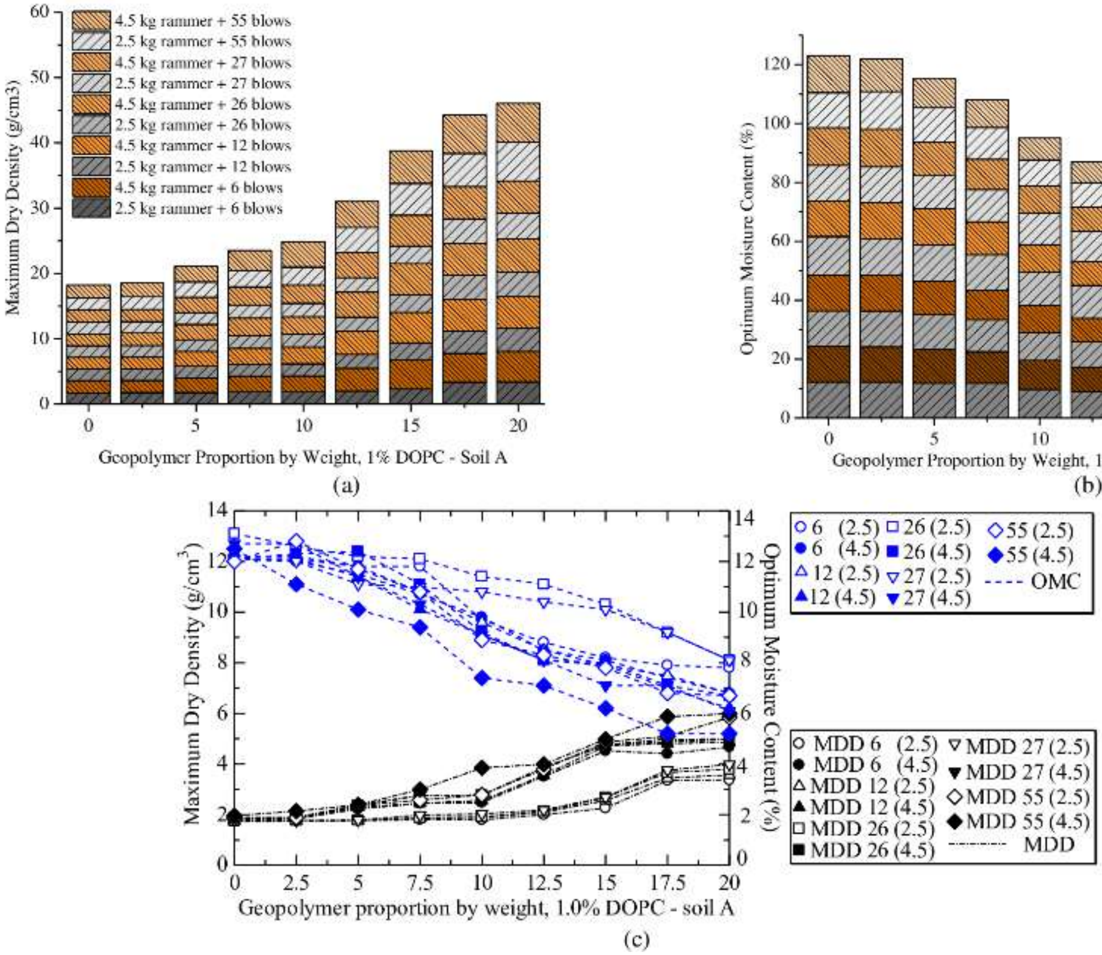


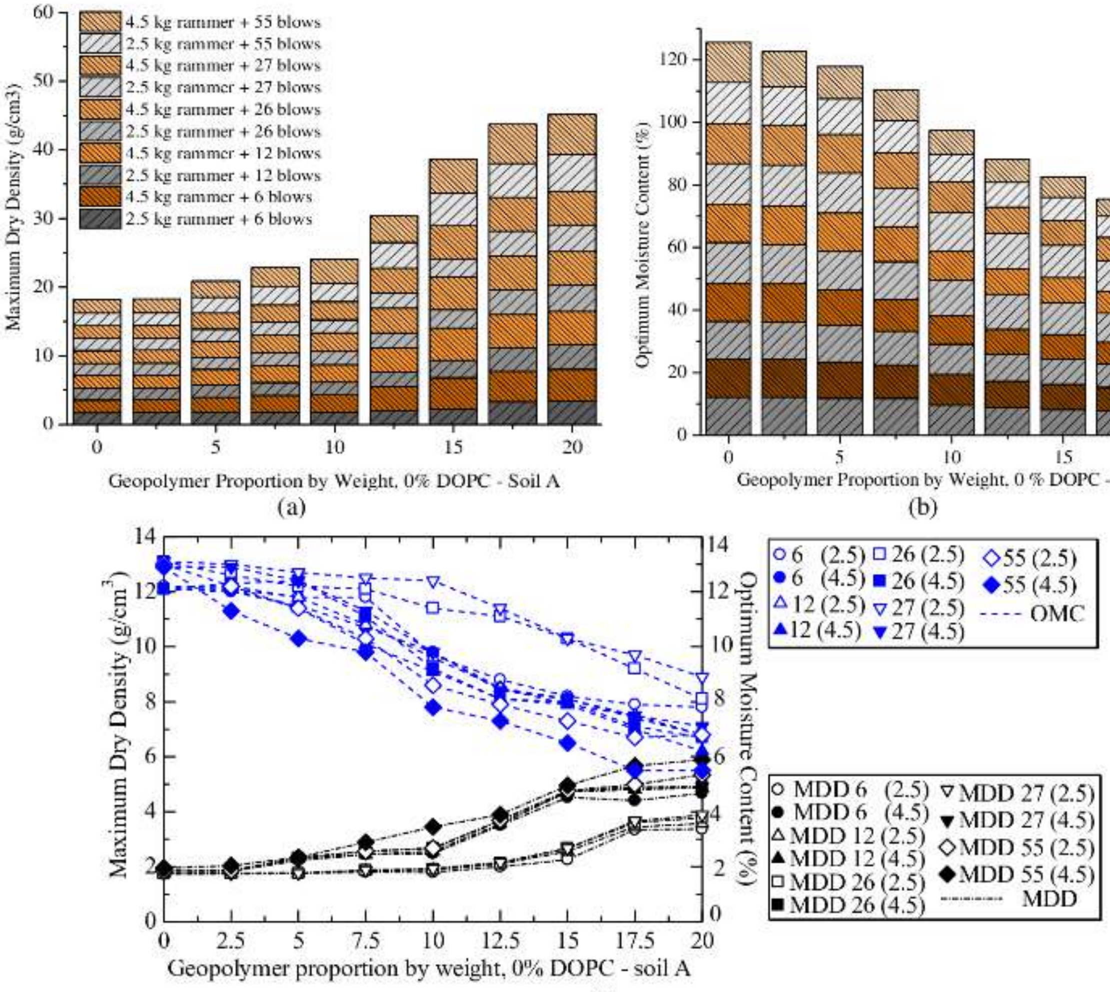
FIGURE 5

Compaction of Test Soil A at 1.0% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

of treated soil B to that found in soil A, that is having a steady strength density achieved at zero addition of Geopolymer cement under varying compaction blows and compactive efforts. In addition, the use of the higher hammer weight of 4.5 kg along with the longer drop distance involved in the modified proctor mould brought about a greater compaction energy compared to that in standard proctor mould rammer of 2.5kg (Amadi & Eberemu, 2012; K. J. Osinubi *et al.*, 2012; Eberemu *et al*., 2013). Analogously, different number of blows of 6, 12, 26, 27, and 55 resulted in different density gain, which increased with increased blows. The influences of various proportions of the quarry dust based Geopolymer cement on compaction behaviour of treated soil B were also examined by adding proportions of Geopolymer cement of 2.5, 5, 7.5 to 20% in that order. Generally, the experimental results show a consistent strength density gained as higher ratios of Geopolymer cement were added into the study soil B. Specifically, a control density of between 1.77 and 3.12 g/cm^3 at zero Geopolymer cement produced densities in the range of 3.38 to 5.89 g/cm^3 at 20% by weight addition of quarry dust base Geopolymer cement under compaction blows of between 6 and 55 as presented in Figures. 7 a, c. The increase in density of treated soil B may firstly be attributed to the increase in applied compaction energies which originated by both hammer weight and numbers of blows per compaction layer. Due to these two weighty factors, the voids between the treated matrixes could be significantly diminished, which in turns increase densification and flocculation of treated soil mass, consequently a higher strength obtain.

Additionally, since the quarry dust based Geopolymer cement is added into the soil B, the voids within the soil mass tend to be filled during the stabilization procedure. Due to pozzolanic properties of the Geopolymer cement which enhances cation exchange reaction, pozzolanic reaction, and polycondensation, the presence of the Geopolymer cement could contribute to the development of density as well as strength of treated soil B.

The effects of ordinary Portland cement on the compaction characteristics of treated soil B were also considered. In Figures 8 and 9, the proportions of Portland cement were lowered to 2.5% and 1%, respectively. The aim of adding these



(a) (b)

(c)

FIGURE 6

Compaction of Test Soil A at 0% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

percentages of Portland cement was to bind the test soil at varying proportions of quarry dust based Geopolymer cement. Similar to that found in the treated soil A, compaction behaviour of treated soil B was found almost the same, with a trivial reduced density compared to that was gained at 5% Portland cement cementation. At 0% Portland cement as presented in Figure. 10, the treated soil B gained significant strength because it recorded between 1.74 and 2.95g/cm^3 at zero Geopolymer cement and 3.37 and 5.69g/cm^3 at 20% by weight Geopolymer cement under varying compactive efforts, which were almost the same range of strength density gain at 5, 2.5 and 1% addition of Portland cement (Amadi & Eberemu, 2012; K. J. Osinubi *et al.*, 2012; Eberemu *et al.*, 2013). This experiment research on compaction characteristics of the test soil B treated with quarry dust based Geopolymer cement proving that the quarry dust based Geopolymer cement exhibits the properties which able to partly or even fully take the place of Portland cement in the soil stabilization goal. The optimum moisture content at which these densities were recorded was observed to decrease consistently too over the increased compaction blows and increased proportions of quarry dust based Geopolymer cement.

Effect of Varying Proportions of Quarry Dust based Geopolymer on Cemented and Uncemented Test Soil C under Varying Blows

Similar behaviours as recorded in test soils A and B were also found in the case of soil C, regardless of their different fundamental properties, for example characterization and classification, consistency limits (Atterberg limits) and strength properties (specific gravity, compaction-MDD and OMC). The quarry dust based Geopolymer cement treated soil C demonstrated a consistent strength gain with increased Geopolymer cement at control, 5%, 2.5%, and 1% cementation as presented in Figures 11, 12, 13, and 14. The optimum moisture content at which these densities were recorded was observed to decrease consistently too over the increased

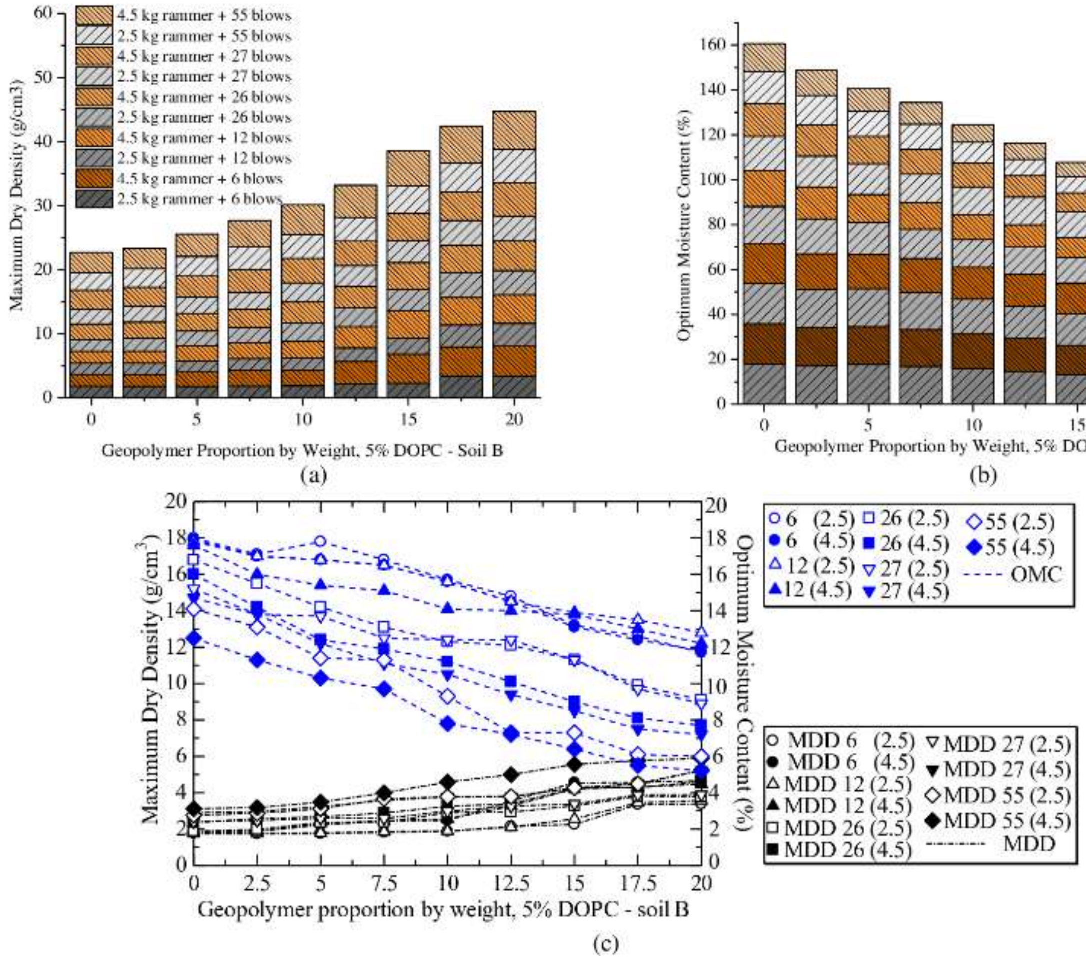


FIGURE7

Compaction of Test Soil B at 5% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

compaction blows and increased proportions of quarry dust based Geopolymer cement. This is due to the increased hydration and carbonation reaction as well as the cation exchange that took place at the adsorbed complex under the influence of the GPC. Due to the additive properties of resisting moisture exposure and sulphate effects, there was a recorded improvement on consistency and strength properties. The binding abilities of the geopolymer cement additive under eco-friendly environments has achieved ecoefficient and sustainable compacted treated soils. Also the addition of the variable proportions of the additive induced the flocculation characteristics of the treated specimens.

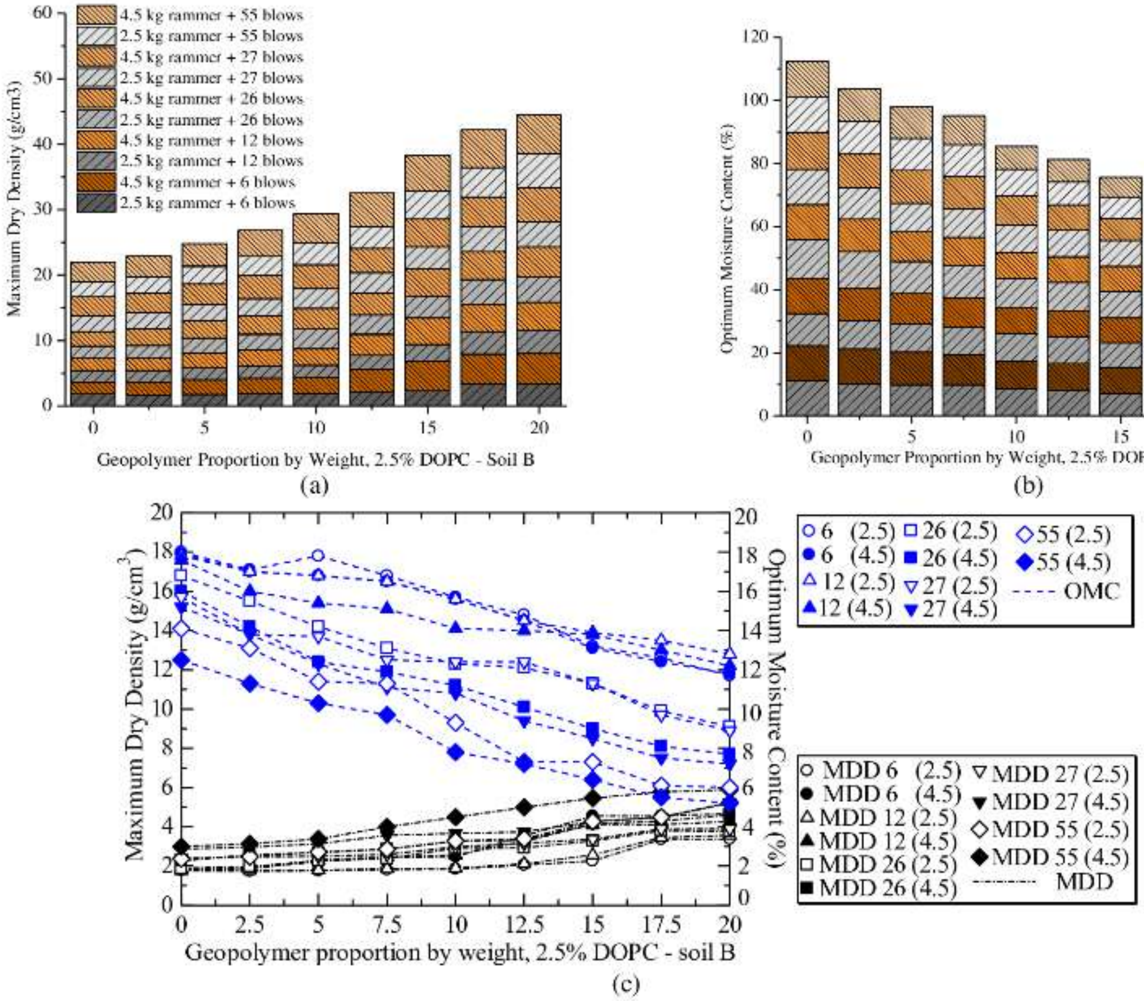
CONCLUSION

Taking into account the results of the laboratory experiments conducted on the quarry dust based Geopolymer cement treated soils A, B and C, it can be concluded with the following remarks:

(a) The alkali-activated (NaOH + Na_2SiO_3) cement produced under dry condition provided the possibility to adapt inorganic waste materials and the properties of such cements are found to be consistently better than those of ordinary Portland cement (OPC) in this study. The concentration of NaOH was kept lower than the concentration of Na_2SiO_3 to check the excessive release of OH^-, which lead to inefficient geopolymerization reaction.

(b) Results from the above procedure showed that the quarry dust based Geopolymer cement treated soils demonstrated significant and consistent strength density improvement with increased compaction blows and rammer weight, and increased proportion of quarry dust based Geopolymer cement.

(c) More important to note is the remarkable strength improvement recorded at 0% Portland cement. This shows that the properties of Geopolymer cement have been fully utilized in the stabilization protocol to achieve a hydraulically bound stabilized material which will possess high compressive strength, high temperature resistant of above 600°C, resistance to acid, salts and sulfate attacks, and resistance to brittle and corrosion effects. This behavior may be attributed to the properties of the constit-



(a)

(b)

(c)

FIGURE 8

Compaction of Test Soil B at 2.5% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

uent elements of the Geopolymer cement where ground granulated blast furnace slag produces high level of calcium and quarry dust produces high concentration of aluminosilicates, which contribute to strength gain by calcinations, cation exchange, hydration reactions and polycondensation. In addition to the strength density gain, the moisture content at which the densities were achieve was recorded and this reduced consistently also with increased proportion of the Geopolymer cement.

(d) The consistent increase in strength recorded at increased proportion of the quarry dust based Geopolymer cement showed that at amount of larger 20% by weight addition of the Geopolymer cement, the soils will continue to densify and flocculate thereby building more strength properties satisfactory for use as stabilization materials. Generally, solid waste materials such as quarry dust, fly ash, ground granulated blast furnace, etc. have shown again to be good combinations as geomaterials formation utilized in the improvement of geomaterials as foundation materials.

ACKNOWLEDGEMENT

The authors gratefully acknowledge Prof. Wei Wu, Head of Institute of Geotechnical Engineering, University of Natural Resources and Life Science (Vienna, Austria) for his exceptional comments on the present work. This work was supported by the Ministry of Education and Training of Vietnam based on the decision No. 5652/QD-BGDDT on December 28, 2018, with a project number B2019-MDA-08.

CONFLICT OF INTEREST

There is no conflict of interests recorded in this research.

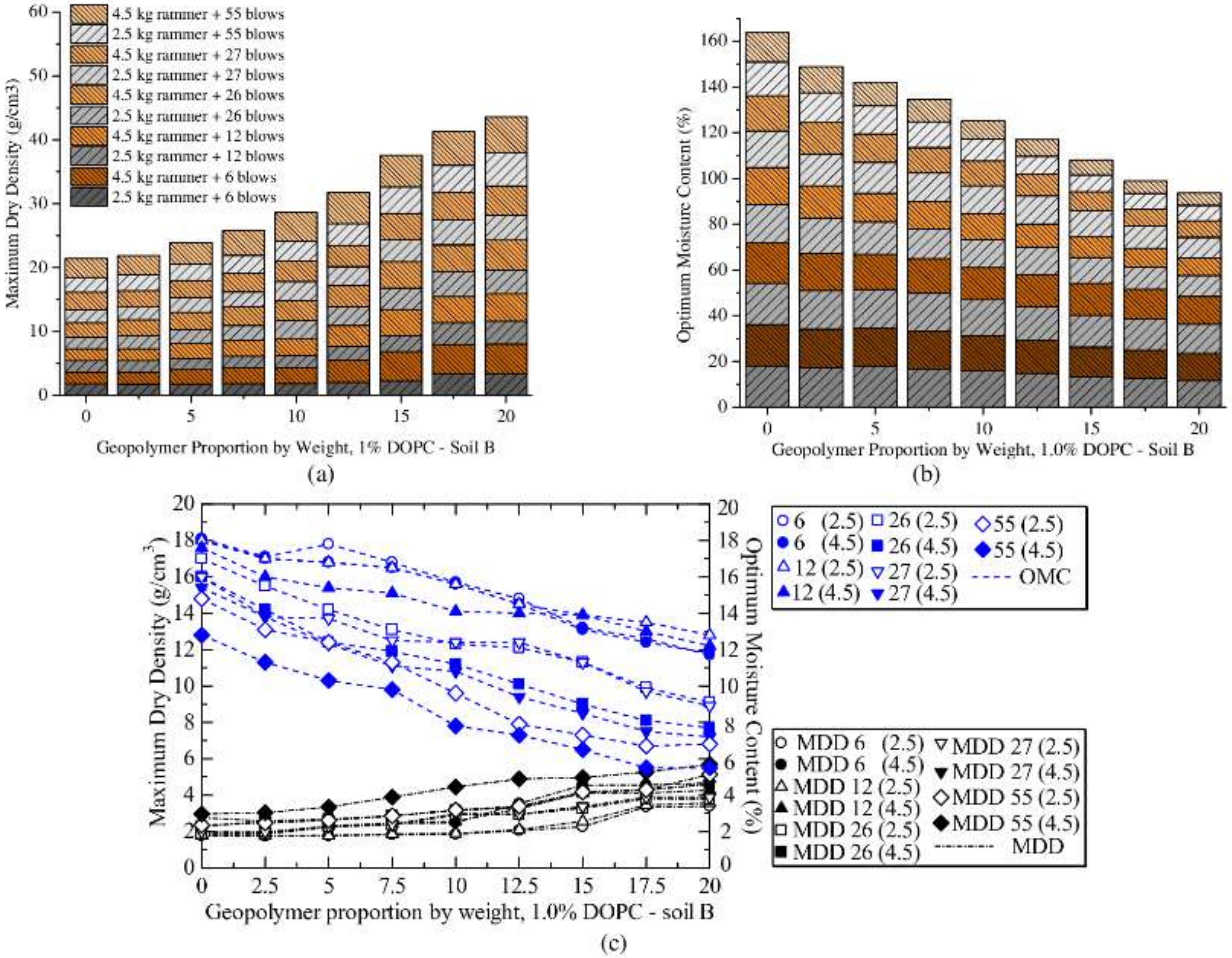


FIGURE 9

Compaction of Test Soil B at 1% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

REFERENCES

Abdel-Gawwad, H., & S. Abo-El-Enein, (2016). A novel method to produce dry geopolymer cement powder. *HBRC Journal*, 12(1), 13-24.

Akbari, H., R. Mensah-Biney, & J. Simms, (2015). Production of Geopolymer Binder from Coal fly ash to make cement-less concrete. Paper presented at the World of Coal Ash (WOCA) Conference in Nasvhille, TN-May.

Amadi, A.A. & A.O. Eberemu, (2012). Delineation of compaction criteria for acceptable hydraulic conductivity of lateritic soil-bentonite mixtures designed as landfill liners. *Environmental Earth Sciences*, 67:999–1006. DOI 10.1007/s12665-012-1544-z

American Association of State, H., & Transportation, O. (1993). AASHTO Guide for Design of Pavement Structures. Washington, D.C.: American Association of State Highway and Transportation Officials.

Bromley, L., & D. Hadfield, (2017). Geotechnical Asset Management: How Structural Engineers Can Exploit Geo-Polymer Injection Technology. URETEK Technical Report.[online].

BS 1377 - 2. (1990). Methods of test for soils for civil engineering purposes. British Standards Institution,London, England.

BS 1924 - 2. (1990). Methods of test for cement-stabilized and lime-stabilized materials. British Standards Institution, London, England.

BS 5930. (2015). Methods of Soil Description. British Standard Institute, London, England.

Bui Van, D., K.C. Onyelowe, & M. Van Nguyen, (2018). Capillary rise, suction (absorption) and the strength development of HBM treated with QD base geopolymer. *International Journal of Pavement Research and Technology*. DOI:https://doi.org/10.1016/j.ijprt.2018.04.003

Bykkam, S., M. Ahmadipour, S. Narisngam, V.R. Kalagadda, & S.C. Chidurala, (2015). Extensive studies on X-ray diffraction of green synthesized silver nanoparticles. *Advances in nanoparticles*, 4(01), 1-10.

Damilola, O.M. (2013). Syntheses, characterization and binding strength of geopolymers: A review. *Int. J. Mater. Sci. Appl*, 2(6), 185-193.

Davidovits, J. (2013). Geopolymer cement. A review. Geopolymer Institute, Technical papers, 21, 1-11.

Eberemu, A.O., (2013). Evaluation of bagasse ash treated lateritic soil as a potential barrier material in waste con-

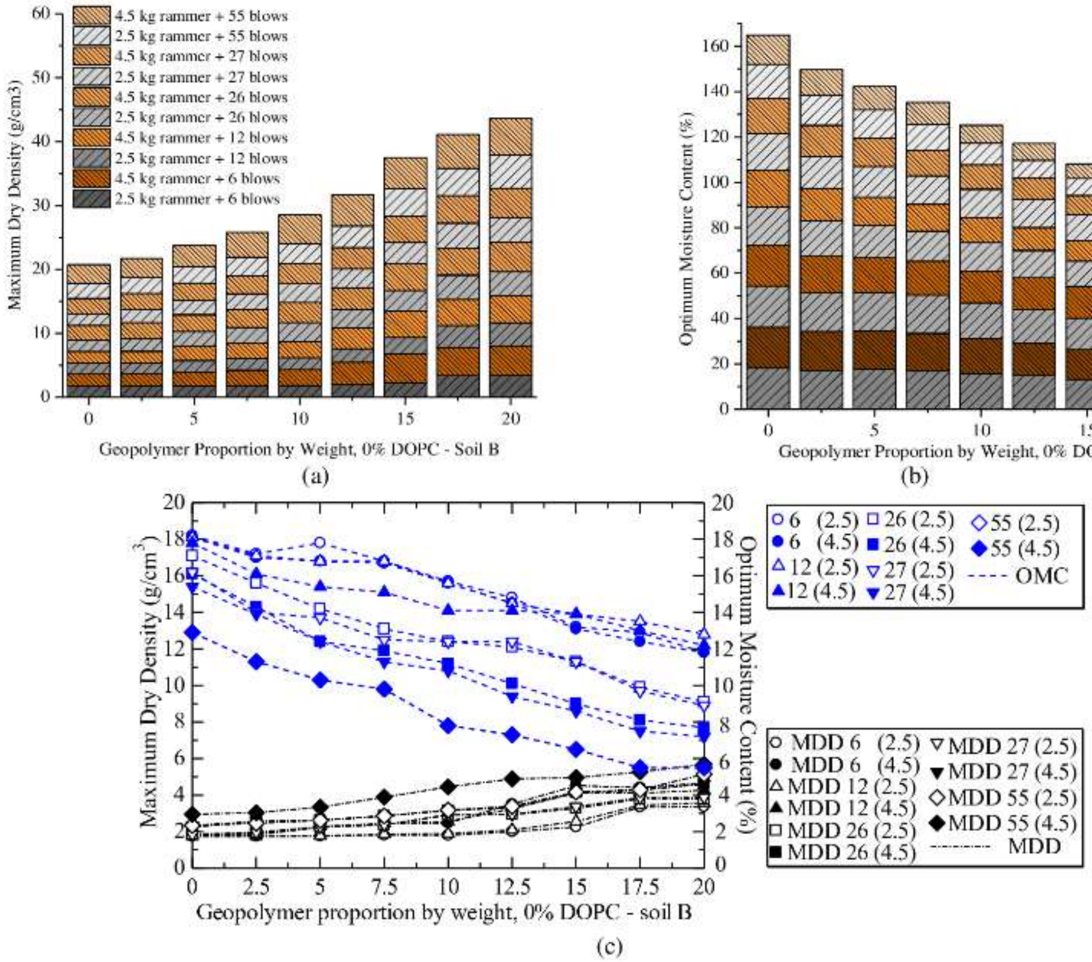


FIGURE 10

Compaction of Test Soil B at 0% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying

tainment application. *Acta Geotechnica*, DOI 10.1007/s11440-012-0204-5

Eberemu, Adrian O., Joseph E. Edeh, & A.O. Gbolokun, 2013. The Geotechnical Properties of Lateritic Soil Treated with Crushed Glass Cullet. *Advanced Materials Research*, Vol. 824, pp 21-28. doi:10.4028/www. scientific.net/AMR.824.21

Eberemu, A.O. & K.J. Osinubi, 2010. Comparative Study of Soil Water Characteristic Curves of Compacted Bagasse Ash Treated Lateritic Soil. 6th International Congress on Environmental Geotechnics, 1378-1383, New Delhi, India

Eberemu, Adrian. O., A.A. Amadi, Zaharaddeen A. Garba, B. Ibrahim, Mohammed J. Yusuf, U.S. Hassan, & K.J. Osinubi, (2014). Effects of Curing Period and Compactive Effort on the Swelling Pressure of Expansive Soil. International Conference on Structural and Geotechnical Engineering, Ain Shams University ICSGE 14.

Edeh, J.E., A.O. Eberemu, A.B. Abah, (2012). Reclaimed Asphalt Pavements-Lime Stabilization of Clay as Highway Pavement Materials. *Journal of Sustainable Development and Environmental Protection*, *2 (3), Pp. 62-75.*

Fedrigo, W., W.P. Núñez, T.R. Kleinert, M.F. Matuella, & J.A.P. Ceratti, (2017). Strength, shrinkage, erodibility and capillary flow characteristics of cement-treated recycled pavement materials. *International Journal of Pavement Research and Technology*, 10(5), 393-402.

Fwa, T.F. (2005). The handbook of highway engineering: CRC Press.

Ghosh, P., H. Kumar, & K. Biswas, (2016). Fly ash and kaolinite-based geopolymers: processing and assessment of some geotechnical properties. *International Journal of Geotechnical Engineering*, 10(4), 377-386.

Gidigasu, M., & J. Dogbey, (1980). Geotechnical characterization of laterized decomposed rocks for pavement construction in dry sub-humid environment. Paper presented at the 6th South East Asian Conf. on Soil Engineering, Taipei, Taiwan.

Hamidi, R.M., Z. Man, & K.A. Azizli, (2016). Concentration of NaOH and the effect on the properties of fly ash based geopolymer. *Procedia engineering*, 148, 189-193.

K.C. Onyelowe, Duc Bui Van, Obiekwe Ubachukwu, Charles Ezugwu, Bunyamin Salahudeen, Manh Nguyen Van, Chijioke Ikeagwuani, Talal Amhadi, Felix Sosa,

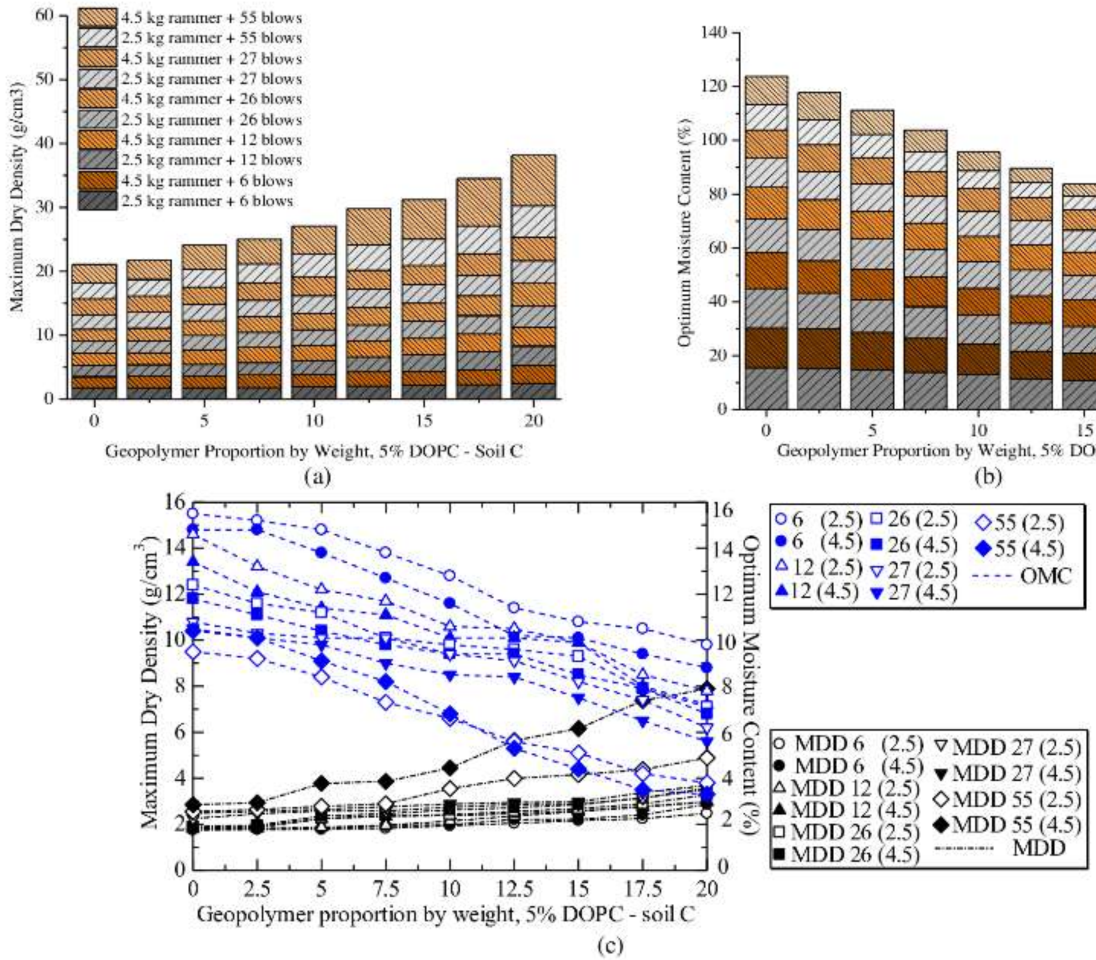


FIGURE 11

Compaction of Test Soil C at 5% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

Wei Wu, Thinh Ta Duc, Adrian Eberemu, Tho Pham Duc, Obinna Barah, Chidozie Ikpa, Francis Orji, George Alaneme, Ezenwa Amanamba, Henry Ugwuanyi, Vishnu Sai, Chukwuma Kadurumba, Subburaj Selvakumar & Benjamin Ugorji, 2019a. Recycling and Reuse Of Solid Wastes; a Hub for Ecofriendly, Ecoefficient and Sustainable Soil, Concrete, Wastewater and Pavement Reengineering. *International Journal of Low-Carbon Technologies*. https://doi.org/10.1093/Ijlct/Ctz028

K.C. Onyelowe, D. Bui Van, C. Ezugwu, T. Amhadi, F. Sosa, F. Orji, G. Aleneme 2019b. Adaptation of Ohia Pozzolan Soil on Cemented Lateritic Soil as Base Material Improvement. Sapienza Università di Roma - Rome, *Italian Journal of Engineering Geology and Environment*. https://doi.org/10.4408/IJEGE.2019-01.O-02

K.C. Onyelowe, D. Bui Van, M. Nguyen Van, C. Ezugwu, T. Amhadi, F. Sosa, W. Wu, T. Ta Duc, F. Orji & G. Alaneme 2019c. Experimental assessment of subgrade stiffness of lateritic soils treated with crushed waste plastics and ceramics for pavement foundation. *International Journal of Low-Carbon Technologies*, 1–18. https://doi.org/10.1093/ijlct/ctz015

K.C. Onyelowe, D. Bui Van, C. Igboayaka, F. Orji, H. Ugwuanyi, 2019d. Rheology of mechanical properties of soft soil and stabilization protocols in the developing countries-Nigeria, *Materials Science for Energy Technologies*, 2(1):8-14. https://doi.org/10.1016/j.mset.2018.10.001

K.C. Onyelowe, A.B. Salahudeen, A.O. Eberemu, C.N. Ezugwu, T. Amhadi & G. Alaneme (2020a). Oxides of Carbon Entrapment for Environmental Friendly Geomaterials Ash Derivation. In book: Recent Thoughts in Geoenvironmental Engineering, Proceedings of the 3rd GeoMEast International Congress and Exhibition, Egypt 2019 on Sustainable Civil Infrastructures – The Official International Congress of the Soil-Structure Interaction Group in Egypt (SSIGE), pp. 58-67. https://doi.org/10.1007/978-3-030-34199-2_4

K.C. Onyelowe, A.B. Salahudeen, A.O. Eberemu, C.N. Ezugwu, T. Amhadi, G. Alaneme & F. Sosa (2020b). Utilization of Solid Waste Derivative Materials in Soft Soils Re-engineering. In book: Recent Thoughts in Geoenvironmental Engineering, Proceedings of the 3rd GeoMEast International Congress and Exhibition, Egypt

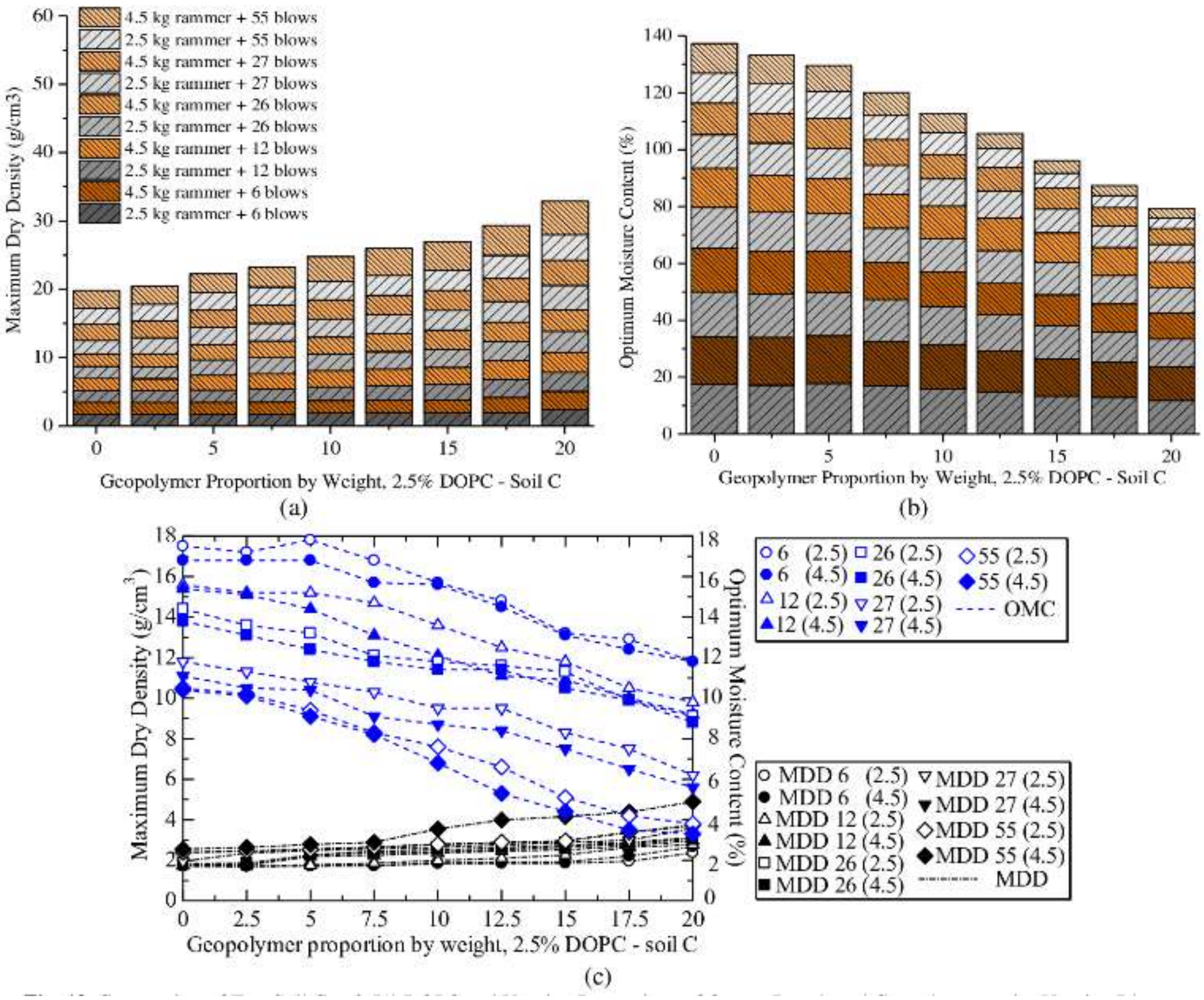


FIGURE 12

Compaction of Test Soil C at 2.5% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

2019 on Sustainable Civil Infrastructures – The Official International Congress of the Soil-Structure Interaction Group in Egypt (SSIGE), pp. 49-57. https://doi.org/10.1007/978-3-030-34199-2_3

K.C. Onyelowe, T. Amhadi, C.N. Ezugwu, E. Onukwugha, H. Ugwuanyi, I. Jideoffor, C. Ikpa, U. Iro & B. Ugorji (2020c). Cemented Lateritic Soil as Base Material Improvement Using Compression. In book: Innovative Infrastructure Solutions using Geosynthetics, Proceedings of the 3rd GeoMEast International Congress and Exhibition, Egypt 2019 on Sustainable Civil Infrastructures – The Official International Congress of the Soil-Structure Interaction Group in Egypt (SSIGE), pp. 58-67. https://doi.org/10.1007/978-3-030-34242-5_4

K.J. Osinubi, A.O. Eberemu, A.O. Bello, & A. Adzegah, 2012. Effect of Fines Content on the Engineering Properties of Reconstituted Lateritic Soils in Waste Containment Application. *Nigerian Journal of Technology (NIJOTECH)*, 31 (3), pp. 277-287.

K.J. Osinubi & A.O. Eberemu, 2013. Hydraulic conductivity of compacted lateritic soil treated with bagasse ash. International *Journal of Environment and Waste Management*, 11 (1), 38-58.

K.J. Osinubi, Adrian O. Eberemu & Agapitus A. Amadi, 2012. Compatibility of compacted lateritic soil treated with bagasse ash and Municipal Solid Waste leachate. *International Journal of Environment and Waste Management*, 10 (4), 365-376.

Meegoda, N. J., & P. Ratnaweera, (1994). Compressibility of contaminated fine-grained soils. *Geotechnical Testing Journal*, 17(1), 101-112.

Mubayi, A., S. Chatterji, P.M. Rai, & G. Watal, (2012). Evidence based green synthesis of nanoparticles. *Adv Mat Lett*, 3(6), 519-525.

NGS. (1997). Testing for the selection of soil for roads and bridges. Nigeria General Specification, Vol II.

Nikolov, A., Rostovsky, I., &Nugteren, H. (2017). Geopolymer materials based on natural zeolite. *Case Studies in*

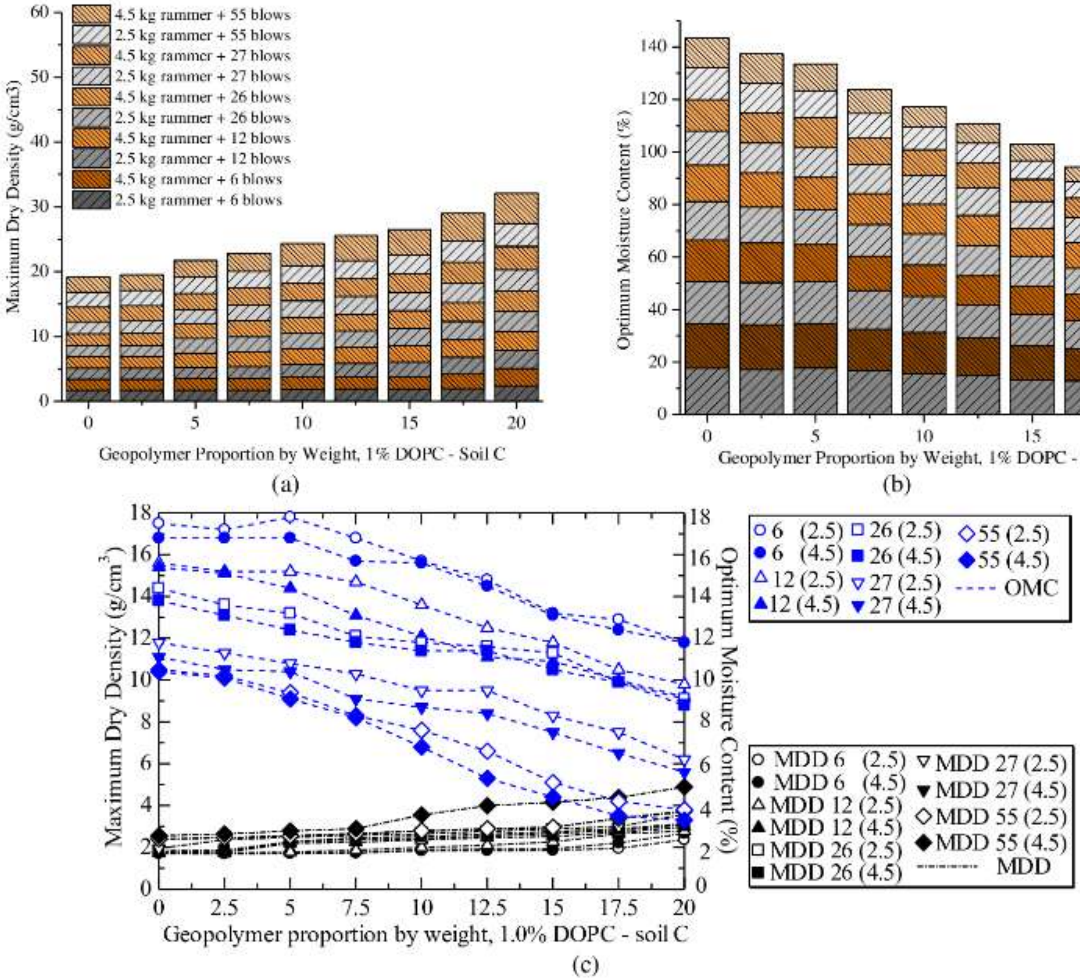


FIGURE 13

Compaction of Test Soil C at 1% DOPC and Varying Proportions of Quarry Dust based Geopolymer under Varying Blows

Construction Materials, 6, 198-205. DOI:https://doi.org/10.1016/j.cscm.2017.03.001

Nnochiri, E.S., & O.M. Ogundipe, (2016). Geotechnical Properties of Lateritic Soil Stabilized with Ground-Nut Husk Ash. *Civil Engineering Journal*, 2(11), 568-575.

Onyelowe, K. (2017a). Nanostructured waste paper ash stabilization of lateritic soils for pavement base construction purposes. *Electronic Journal of Geotechnical Engineering*, 22(09), 3633-3647.

Onyelowe, K. (2017b). Nanostructured waste paper ash treated lateritic soil and its california bearing ratio optimization. *Global J TechnolOptim*, 8, 220.

Onyelowe, K., & F. Okafor, (2015). Review of the Synthesis of nano-sized ash from local waste for use as admixture or filler in engineering soil stabilization and concrete production. *Journal of Water and Environmental Nanotechnology*, 4(4), 23-27.

Onyelowe, K.C. (2017). Nanosized palm bunch ash (NPBA) stabilisation of lateritic soil for construction purposes. *International Journal of Geotechnical Engineering*, 1-9. DOI: https://doi.org/10.1080/19386362.2017.1322797

Onyelowe, K.C., & B.V. Duc, (2018). Durability of nanostructured biomasses ash (NBA) stabilized expansive soils for pavement foundation. *International Journal of Geotechnical Engineering*, 1-10. DOI:10.1080/19386362.2017.1422909

Osinubi, K.J., J.R. Oluremi, A.O. Eberemu, & S.T. Ijimdiya, (2017). Interaction of landfill leachate with compacted lateritic soil–waste wood ash mixture. Proceedings of the Institution of Civil Engineers, *Waste and Resource Management*, 170, Issue WR3+4, 128–138 https://doi.org/10.1680/jwarm.17.00012

Osinubi, K. (2000). Laboratory trial of soil stabilization of Nigerian black cotton soils. *Nigerian Society of Engineers Technical Transactions*, 35(4), 13-21.

Osinubi, K.J. & A.O. Eberemu, (2008). Effect of Desiccation on Compacted Lateritic Soil Treated with Bagasse Ash. Materials Society of Nigeria (MSN) Zaria Chapter Book of Proceedings, 4th Edition. Pp. 1-10.

Osinubi, K.J. & A.O. Eberemu, (2019). Compatibility and Attenuative Properties of Blast Furnace Slag Treated Laterite. *Journal of Solid Waste Technology and Management*, 35(1 8), P*p. 7-16.*

Osinubi, K., V. Bafyau, & A. Eberemu, (2009). Bagasse ash stabilization of lateritic soil. In Appropriate Technologies for Environmental Protection in the Developing World, pp. 271-280, Springer, Dordrecht.

Raki, L., J. Beaudoin, R. Alizadeh, J. Makar, & T. Sato, (2010). Cement and concrete nanoscience and nanotechnology. *Materials*, 3(2), 918-942.

Salahudeen, A.B., A.O. Eberemu, & K.J. Osinubi, 2014. Assessment of Cement Kiln Dust-Treated Expansive Soil for the Construction of Flexible Pavements. *Geotechnical and Geological Engineering, an International Journal*, 32:923-931. DOI 10.1007/s10706-014-9769-0

Škvára, F., T. Jílek, & L. Kopecký, (2005). Geopolymer materials based on fly ash. *Ceram.-Silik*, 49(3), 195-204.

Srinivasan, K., & A. Sivakumar, (2013). Geopolymer binders: a need for future concrete construction. *ISRN Polymer Science*, volume 2013, Article ID 509185, 8 pages. DOI: http://dx.doi.org/10.1155/2013/509185

Van Duc, B., & O. Kennedy, (2018). Adsorbed complex and laboratory geotechnics of Quarry Dust (QD) stabilized lateritic soils. *Environmental Technology & Innovation*, 10, 355-363. DOI:https://doi.org/10.1016/j.eti.2018.04.005

Xiao, Y., Z. Cai, Z. Wang, B. Lai, & Y. Chu, (2005). An X-ray nanodiffraction technique for structural characterization of individual nanomaterials. *Journal of synchrotron radiation*, 12(2), 124-128.

Zain, H., M.M.A.B. Abdullah, K. Hussin, N. Ariffin, & R. Bayuaji, (2017). Review on various types of geopolymer materials with the environmental impact assessment. Paper presented at the MATEC Web of Conferences, Vol. 97, p. 01021. EDP Sciences.