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ORIGINAL PAPER

Assessment of compressive strength, durability, and erodibility of quarry dust-based geopolymer cement stabilized expansive soil

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Abstract

The effect of quarry dust-based geopolymer cement on the compressive strength, erodibility, and durability potential of expansive soils has been studied under laboratory conditions. The particular interest was on the geopolymer cement treatment of soils subgrade under hydraulically bound environments. Lateritic soils, which form the compacted foundation of pavements, tend to swell upon contact with moisture and shrink during the drying periods. These two factors affect the response and overtime performance of foundation infrastructure. On the other hand, underground and side rail surface flows affect badly constructed pavements by eroding dislodged foundation materials. However, the need to study the erodibility response of the foundation materials exposed to moisture movements has given rise to the present study. The soils classified as A-7–6, A-7–5, and A-7–5 soils according to AASHTO classification, which are highly plastic and expansive were treated with 10–120% by dry weight of soil and the effect on the compressive strength and durability was studied. Conversely, 10–150% by dry weight was used to study the erodibility response of the treated soils. Both treated frequencies were done at the rate of 10%. The treatment protocol showed that the geopolymer cement (GPC) consistently improved the compressive strength, erodibility, and durability of the treated soils. The results have shown that the green cement has improved the properties of the compacted earth utilized under moisture-bound environment and show the potential to be used as an alternative and sustainable binder for earthworks.

Keywords Soil erodibility · Compressive strength · Quarry dust · Moisture bound materials · Solid waste recycling · Durability · Sustainable geotechnics

1 Introduction

Under zero confining stress, lateritic soils utilized as compacted subgrade resist axial load or compressive stress, the maximum of which is known as the unconfined compressive strength. This engineering phenomenon is relevant in the design and construction of subgrades of flexible pavements especially when they are subjected to hydraulically bound conditions (Aneke et al. 2019a; Onyelowe et al. 2021b). In the case of problematic soils, which are commonly encountered in the field, their unconfined compressive strength (UCS) usually falls below the permissible value, hence requires modification and stabilization to improve its ability to resist compressive stress and erodible conditions. It is also important to note that the UCS is a key parameter in the evaluation of the durability of compacted subgrade earth, especially when the loss of strength on immersion method is used during design. This is because, it explains the effect of the rise and fall of the water table, which expose the compacted sub-

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grade to soak-dry cycles throughout the seasons (Aneke et al. 2019b; Onyelowe et al. 2021a, b). Hence, it is important to study the UCS behavior of the lateritic soils before they are used as subgrade materials especially if they are exposed to moisture ingress to establish the durability of the infrastructures.

On the other hand, when compacted subgrade is constantly exposed to soak-dry and swell-shrink cycles, the inter-particle forces begin to separate by the weakening of the soil Van der Waal's force. This phenomenon causes the subgrade mass of soil to detach and deposit. This affects the erodibility of the subgrade structure. On a general note, when compacted subgrade soil or lateritic soil, which is used as a foundation material possesses properties like UCS, durability, and erodibility that don't meet the basic design requirements, the soil is said to be problematic and requires stabilization. In the past, the use of conventional Portland cement to improve the engineering qualities of weak lateritic soils has been common with its merits and demerits.

However, in recent years, the utilization of quarry dust in the improvement of soil for construction works has been on the increase (Van and Onyelowe 2018; Van et al. 2018; Onyelowe et al. 2020). The improvement exercise has focused on the consistency, shrinkage and swelling, compaction, and strength characteristics of weak soils. This is precisely and fundamentally achieved through the valorization of solid waste materials as well as activation of class F fly ash to achieve the desired pozzolanic geomaterial (Aneke et al. 2019c) needed for soil cementation. Shrinkage and swelling characteristics are properties that are dependent on lateritic soils' exposure to moisture or water intake during wet and dry cycles. For construction materials, especially geomaterials, which are utilized in a hydraulically bound medium, it is important to study their shrinkage and swelling behavior or response to exposure to the moisture-bound environment (Bromley and Hadfield 2017; Arioz et al. 2006; Onyelowe et al. 2012a, b, c). This is essential in the case of pavement foundations, airfield foundations, rail track foundations, landfills, etc.

The durability potential of the lateritic soils treated with these geomaterials is equally studied because of its dependence on the structures' performance duration on exposure to moisture effects. This is because of the effect, moisture exposure has on the life of geomaterials and hydraulically bound facilities like the pavement subgrade as well as all other sub-structural constructions. Similarly, erodibility is a soil property that examines its ability to resist erodible forces when exposed to moisture movement, runoff or erosion. Weak or soft soils erode when the erosive force (moisture movement) is greater in magnitude than the contact, inter-particle or binding force within the soil matrix (Onyelowe and Okafor 2012a, b; Onyelowe 2013; Onyelowe et al. 2020).

The treatment of lateritic soils with amorphous materials or supplementary binders of various forms and compositions increases the binding energy in the soil matrix. This exercise makes it difficult or impossible for treated soils to be eroded over time; hence the durability of constructed facilities is also improved. Closer studies and examination have shown that quarry dust, although a solid waste from quarrying operations, is rich in aluminosilicates. The aluminosilicates are the compounds responsible for pozzolanic reactions, calcination reactions, hydration reactions; strength development and flocculation in the soil during a stabilization protocol (Onyelowe 2015, 2017a; Onyelowe and Ubachukwu 2015). Due to global warming and environmental hazards and degradation caused as a result of CO_2 emissions, efforts have been made by construction experts in geotechnical engineering to reduce the use of non-ecofriendly construction materials to zero (Hoy et al. 2016; Onyelowe and Agunwamba 2011, 2012a, b; Onyelowe and Van 2018a, b, c; Onyelowe et al. 2018a, b, c).

Construction activities that still encourage the use of Portland cement and other forms of chemical-based cement contribute daily to global warming. This is because an equivalent amount of CO_2 is released into the atmosphere when cement is used for any construction purpose. However, the environment suffers from the indiscriminate release of solid waste (Onyelowe 2017a, 2018, b, c, d, e, f, g, h, i) from agricultural and industrial processes. The operational measure of recycling waste materials into geomaterials and their utilization in the improvement of soft and expansive soils is of great concern to this work (Onyelowe 2011, 2012a). Various materials obtained through the direct combustion of solid waste materials have been in use to improve the mechanical properties of weak or expansive soils for construction purposes like palm bunch ash, bagasse ash, paper ash, recycled tire ash, egg shell ash, etc. (Onyelowe and Maduabuchi 2017a, b, c; Onyelowe 2012b, c). Results have shown that these amorphous materials when added in varying proportions increase the strength and durability properties of treated soils (Van et al. 2017, 2018). Laboratory studies on the durability of ash-treated lateritic soils have also shown a great improvement in the erodibility and durability index potential of soils with increased additive (ash) proportion.

Further on the effort of achieving improved soil properties, an enhanced composite binder called geopolymer cement has been developed (Phummiphan et al. 2016). Geopolymer cements are a composite combination of materials first developed by Joseph Davidovits. In the present research work, it is made of waste materials which are quarry dust, and metallurgical slag blended together under the activation effects of alkali compounds. This procedure synthesized an eco-friendly geomaterial utilized as a binder in the stabilization or soil improvement procedures (Phummiphan et al. 2016; Abdel-Gawwadm and Abo-El-Enein 2016). They are products of geopolymerization reactions, which have been observed to possess high acid resistance; high-temperature resistance beyond 600 °C, resistant to the corrosive action of salts, and frost activity (Hoy et al. 2016; Abdel-Gawwadm and Abo-El-Enein 2016).

The utilization of geopolymer cement synthesized from quarry dust and metallurgical slag with alkali activators of silicates in the improvement of lateritic soil properties is the main aim of this study with particular focus on; (1) effect of the geopolymer cement on the unconfined compressive strength (UCS) and erodibility potential of the treated soil and (2) effect of the geopolymer cement on the durability potential of the treated soil. The valorization of solid waste to get amorphous ash as a geomaterial has been utilized in green geotechnical engineering and primarily in the improvement of soil-based foundation materials. Additionally, the synthesis of geopolymer cement as a replacement for conventional cement to achieve sustainable and green construction devoid of the excessive release of oxides of carbon during construction processes is also a novel and fundamental goal of this research work.

2 Materials preparation and experimental methods

2.1 Materials preparation

Three different borrow pit locations, with coordinates of 5° 29′ 16" North and 7° 28′ 58" East (Olokoro location), 5° 27′ 0" North and 7° 31′ 60" East (Amaba location), and 5° 31′ 0" North and 7° 26′ 0" East (Ohia location), were the source point of the test soils. Soil sampling was achieved by the conventional method using a pick and shovel. Lumps were eliminated by tapping with a rubber pestle and open air-dried for 4 days to the start of the experiment procedure. Quarry dust and metallurgical slag were collected as wastes from quarry sites and steel companies respectively. The sodium oxide and silicates were secured from chemical shops and used as alkali activator materials.

2.2 Experimental methods

Preliminary conventional tests, particle size distribution, Atterberg limits, compaction, free swell test, and shrinkage limit tests were conducted to determine the basic properties of the test soils following the British standards (BS 1377 1990; BS 1924 1990) and the Nigerian specifications (NGS 1997). The reference soil was treated with the geopolymer cement in the dosage of 10–150% at the rate of 10% to study the erodibility behavior. Erodibility cylindrical test samples of dimensions 152 mm in diameter and 114 mm in height using the CBR mould were compacted in five layers. After extracting the compacted specimens from the mould after 3 days to gain minimum strength, folded in moist paper and aluminum foil, they are cured for 14 days at room temperature. Two specimens were prepared for one treated matrix, which gave a total of 30 test specimens. The applied methods presented in Australian protocol TMT186 (Roads and Maritime Services 2012) were adopted. After the open curing protocol, the test matrixes were kept in a constant water level at a 25.5 mm metal container for 1 h. For modeling and simulating traffic pressure, surcharges similar to those used in the California Bearing Ratio test with a mass of 6750 g were fixed on the top of the test specimens. Test specimens and surcharges were placed in a metal watertight container with 200.1 mm in diameter filled with 200 ml of moisture exposure. The metal container was secured to a vibrating platform and the test samples were vibrated for 10 min. Test specimens and metal container were washed and then the washing water was wet sieved over a 2.36 mm sieve. The detached and eroded fine materials passing the 2.36 mm sieve were dried to a constant mass in an oven at a temperature of 55 °C and the results were observed and tabulated. Erodibility, which describes a loss of material, was estimated by dividing the dry weight of the fines in grams by the vibration time at 10 min and expressed in g/min.

The unconfined compressive strength (UCS) values (ASTM D2166-91 1995) and the loss of strength on immersion experiment was proposed in Series 800 (MCHW-V1 2007; Roads and Maritime Services 2012; Shen et al. 2013a, b) using the procedure given in Sect. 880.4. For this case, the reference soil was treated with the geopolymer cement in the dosage of 10–120% at the rate of 10%. Two sets of specimen cylinders with a ratio of diameter 1:1, height was prepared and open-cured for 14 days. While the first group continued open curing at room temperature, the second group of the test cylinders was then cured for an additional 14 days immersed in water also at room temperature. The compressive strength of these immersed specimens (UCS_{imm}) was observed as well as the control specimens ($UCS_{control}$). The control specimens were open-cured for 28 days at room temperature. All curing was undertaken at room temperature. The mixed blend is considered to satisfy durability requirements if the conditions given by the Manual of Contract Documents for Highway Works-V1 (2007) are satisfied.

3 Results and discussions

This section presents the influences of the quarry dust-based geopolymer cement on durability by loss of strength on immersion method, erodibility potentials, and compressive strength of treated lateritic soils. Generally, the existence of quarry dust in lateritic soils caused the enhancement of unconfined compressive strength of treated soils, with the increasing of quarry dust-based geopolymer cement (QDbGPC) proportion by weight. Additionally, the consistency limits of three different soils were reduced with an increase in additive proportion. Lastly, the influence of quarry dust coupled material on erodibility potential of treated soils was presented.

3.1 Materials characterization

Fundamental properties, particle size distribution, and chemical compound composition of the three studied soil specimens and test materials are presented in Tables 1 and 2, Figs. 1 and 2. The test soils have high free swell indexes and low shrinkage limits (BS 5930 2015; Onyelowe and Okafor 2015; Onyelowe and Onuoha 2016; Onyelowe et al. 2020). This desiccation behavior makes the soils unsuitable as a foundation material. Exposure of these untreated soils to moisture for a long time creates room for the failure of infrastructures constructed with these soils because of their high potential to swell. It is also observed that the soils are highly plastic (with PI > 17% as presented in Fig. 1). This property also makes the untreated material unsuitable to be utilized as subgrade materials or as hydraulically bound materials. The soils are classified as A-7–6, A-7–5, and A-7–5 group of soils and are observed to be poorly graded soils (AASHTO 1993). Soils A and C contain 58.5% and 56% of clay and are designated as high clay (CH) content soils, which is a property responsible for the expansivity of clayey soils in contact with moisture. Table 2 shows that the test materials have a high percentage of aluminosilicate compounds, which resulted from an XRF exposure. Quarry dust (QD) also contains high pozzolanic property in accordance with materials standard for pozzolanas (ASTM C618 1978). The quarry dust-based geopolymer cement was synthesized according to the procedures and findings of Davidovits and utilized by other research methods (Onyelowe and Okafor 2015; Akbari et al. 2015; Davidovits 2013; Abdel-Gawwadm and Abo-El-Enein 2016; Onyelowe et al. 2020). The aluminosilicate materials required to materialize the geopolymer cements consist of quarry dust. The geopolymer type of cement synthesis was activated by the reactive stimulus of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) mixed in the ratio of 1:1 (Nikolov et al. 2017; Onyelowe 2016a, b, c; Skvara et al. 2005; Srinivasan and Sivakumar 2013; Onyelowe et al. 2016). According to previous research findings, a molarity concentration of NaOH of 12 M was used to achieve an environmentally friendly material handling and construction process. Also, it was important to keep the dosage of sodium compounds at a low level of not more than 5% so that better strength properties of geopolymer cement might be attained. The synthesis of geopolymer matrixes was carried out by mixing these above materials in a proportion of 4.8% activa-

Table 1 Basic properties of soils

Property description of test soils and units	Values/descriptions		
	Soil (A)	Soil (B)	Soil (C)
% Passing Sieve, no. 200	58.5	51	56
NMC (%)	12.1	13.49	14
LL (%)	40	46	64
PL (%)	18	21	36
PI (%)	22	25	28
FSI (%)	38.5	33.4	37.1
AASHTO classification	A-7–6	A-7–5	A-7–5
USCS	CH	CH	CH
MDD (g/cm^3)	1.76	1.85	1.80
OMC (%)	13.1	16.2	13.13
Color	Reddish brown	Reddish gray	Reddish ash

Table 2 Chemical oxide compounds composition of the materials used in this study

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	–	–	–	–

IR is insoluble residue, *LOI* is loss on ignition, *bQD* quarry dust

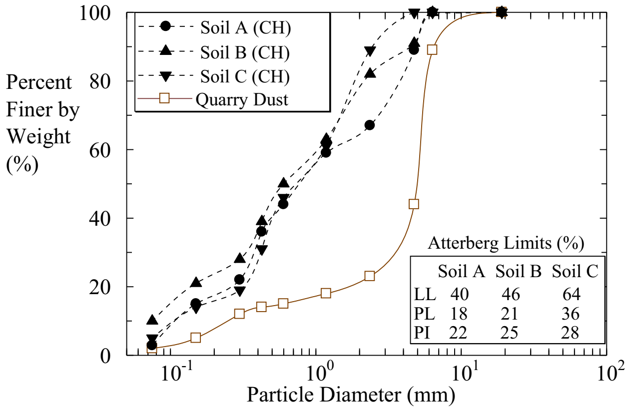


Fig. 1 Grain size distribution of studied materials

tor, plus 80% quarry dust by weight and 15.2% metallurgical slag by weight (Soosan et al. 2005).

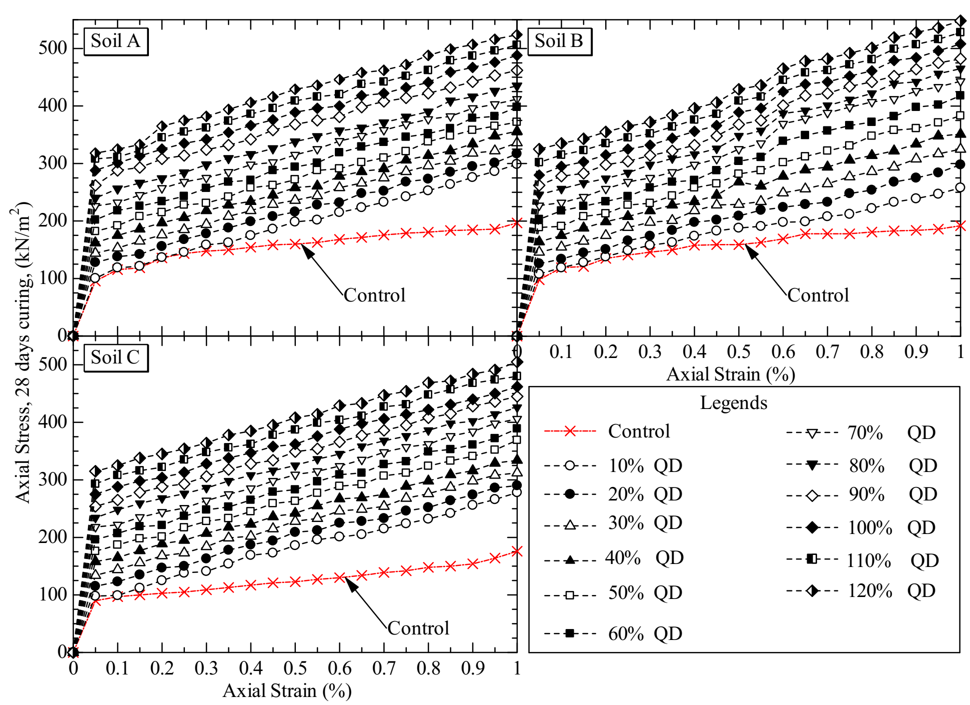
3.2 Compressive strength behavior

The compressive strength behavior of the quarry dust-based geopolymer cement-treated lateritic soils cured for 28 days was presented in Fig. 2. The graphs show almost similar behavior of the soils under the QDbGPC treatment. The figures showed the resistance of the soil to yield at the beginning of the loading depicted by the initial higher slope and changes with increased loading. It was important to cure for a long period of 28 days to ascertain the behavior of the treated soils under a long period of exposure to moisture. The treated soils A, B, and C blended with the geopolymer cement remarkably improved the compressive strength. The high proportion of aluminosilicates contained in the admixture in the stabilization contributed to this substantial improvement behavior, which agrees with previous findings (Onyelowe et al. 2021a, b, c; Phummiphan et al. 2016). This possessed the ability to reduce adsorbed moisture in the polymerization process, thereby causing CH soils to perform like granular soils. This is also attributed to the physicochemical and high pozzolanic characteristics of the geopolymer cements (Aneke et al. 2015; Fedrigo et al. 2017; Shen et al. 2013a, b, 2017; Gidigasu and Dogbey 1980). The compounds of the synthesized geopolymer cement, at high concentration may have equally increased the contact force or interconnection between soil particles to produce a highly homogenous material (AASHTO 2014; Onyelowe 2012b, c; Fwa 2006).

3.3 Compressive loss of strength on immersion and durability potential

The loss of strength on immersion test results and the associated durability index of quarry dust-based geopolymer cement (QDbGPC) treated lateritic soils are presented in Fig. 3. It presents the behavior of three different lateritic soils treated under laboratory conditions. The initial test on the untreated soils, which served as the reference test, showed that the compacted natural soil was not durable. It showed a durability index of 76.10%, which was less than the standard minimum durability requirement of 80% (Noraida et al. 2015; Onyelowe 2012b, c; Shen et al. 2013a, b, 2017;

Fig. 2 Unconfined compressive strength behavior of treated soils at 28 days curing: Soil A, Soil B, and Soil C



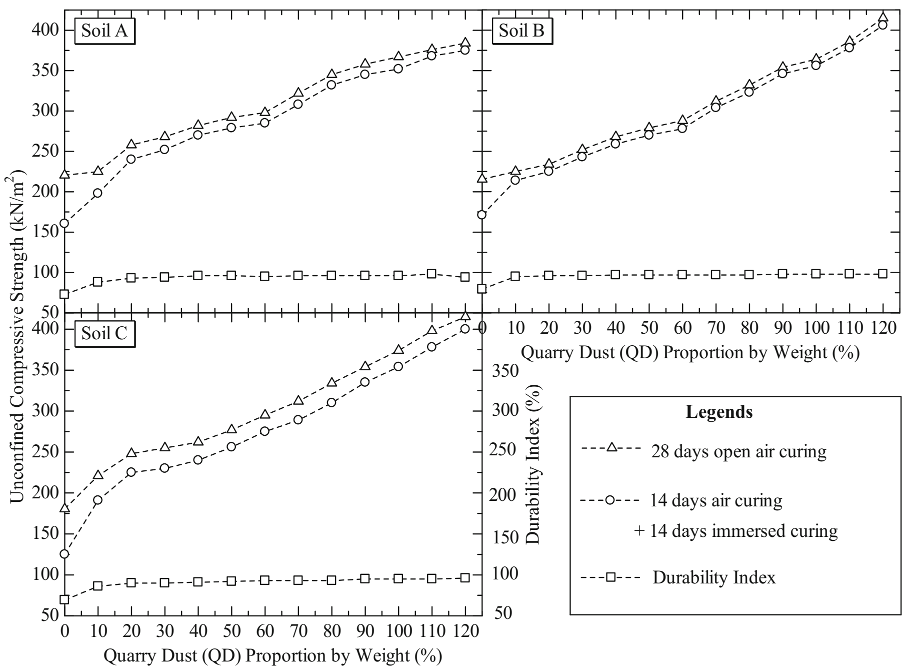


Fig. 3 Effect of quarry dust proportion on compressive strength loss of immersed and durability index of treated soils: Soil A, Soil B, and Soil C

Gidigasu and Dogbey 1980). With the addition of varying rates of quarry dust base geopolymer, the durability potential improved considerably and exponentially from the reference value (76.1%) to, between 81 and 97% for the three soil types. This was with reference to the open-cured and completely immersion-cured sets of treated and untreated specimens. The matric suction on immersion affected the strength development of the treated soils, but the results remained within the minimum 80% durability index requirements. This could be due to the fact that the geopolymer materials showed high pozzolanic characteristics (Hamidi et al. 2016; Van et al. 2018). This resulted from the polymerization of the coupled elements of the synthesized geopolymer cement, which are highly resistant to moisture attack (Onyelowe et al. 2017b). Additionally, this behavior was because of the cations released at the chemical reaction interface that generated a strong resistance to the effect of moisture ingress on immersion. Moreover, the reaction between the soil anions and the geopolymer material cations at the chemical reaction interface contributed to the formation of flocs and progressive densification and gain in strength, which is supported by Onyelowe et al. (2021a, b, c). This behavior also resisted the effect of moisture intake on the immersion of the test specimens. The building up of the pozzolanic reactions by greater polymerization due to geopolymer cement increases improved strength development in the test specimens at different rates. Hence, the property led to an increase in durability potential.

3.4 Effects of quarry dust on soil erodibility of lateritic soils

The average values of particle dislodgement (erodibility), which varied between 12.1 g/min for natural untreated soil and 5.2, 2.5, and 2.7 g/min for soils A, B and C respectively at 150% by weight addition of quarry dust based geopolymer cement (QDbGPC). The geopolymer cement additive and compacting energy may have reduced the erodibility potential. The reduction in the erodibility index for test soil A recorded an average value of 5%, 10% for test soil B, and 6% for test soil C. These recorded rates of reduction were observed between 10 and 90% by weight addition of QDbGPC. With the higher addition of QDbGPC between 100 and 150% by weight, the average erodibility reduction dropped to 4%. Therefore, the use of high geopolymer cement content should be encouraged because it enhances polymerization and calcinations reactions (Onyelowe et al. 2021a). However, the rate at which higher addition reduces the erosion of soil is decreased. Geopolymer cement is highly resistant to shrinkage and eventually inhibits the formation of cracks. This in turn does not promote the ingress of moisture into the pavement structure or underlying subgrade because there are no voids created by the lack of cracks (Van et al. 2017; Shen et al. 2013a, b, 2017; Gidigasu and Dogbey 1980). Consequently, the erosion process is reduced. The reduction in the average erodibility of the GPC treated soil may be due to the fine and reactive surface of the test materials. Additionally, their ability to fill in the voids between soil particles to form flocs and densified matrixes goes a long way in reducing

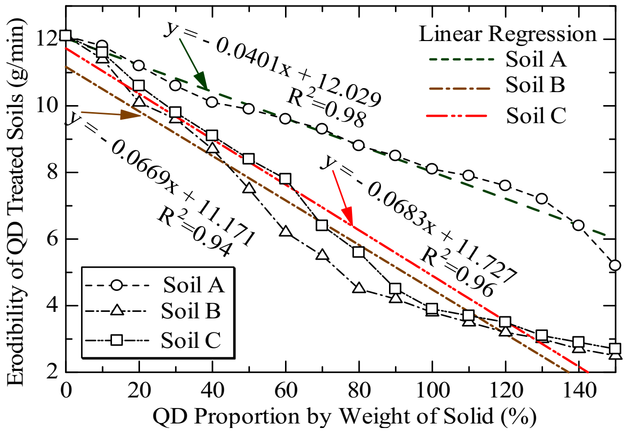


Fig. 4 Effect of quarry dust proportion on erodibility potential of treated soil

the action of erosive forces (Fedrigoet al. 2017; Onyelowe 2012b, c). The reduction in the average erodibility by the addition of the quarry dust base GPC showed the ability to improve the durability of the treated soils under field conditions. Field conditions are exposed to moisture effects or are hydraulically bound. Furthermore, the energy of compaction is another factor to be considered because erodibility depends partly on it (Fedrigo et al. 2017; Shen et al. 2013a, b, 2017; Gidigasu and Dogbey 1980). These results have been achieved without the application of ordinary Portland cement or any other conventional type of binder. Finally, a regression model on the erodibility potential of the quarry dust-based geopolymer cement-treated soils was conducted as presented in Fig. 4. The results showed that test soil A has a regression coefficient of 0.98, with test soils B and C having 0.94 and 0.96 respectively. This shows that soil A rendered the best response to the treatment protocol conducted with quarry dust-based geopolymer compared to soils B and C. The overall erodibility potential behavior of the soils when treated with quarry dust geopolymer cement can be represented as follows:

$$E_{\mathrm{A}} = -0.0401p + 12.029 \quad (1)$$

$$E_{\mathrm{B}} = -0.0669p + 11.171 \quad (2)$$

$$E_{\mathrm{C}} = -0.0683p + 11.727 \quad (3)$$

where E_{A}, E_{B}, and E_{C} are equivalent to the erodibility potential for soils A, B and C and p = QDbGPC percentage by weight.

4 Concluding remarks

The utilization of geopolymer cement, which was synthesized from quarry dust and metallurgical slag with alkali activators of sodium hydroxide and silicates mixed in the ratio of 1:1, in the improvement of lateritic soil properties was studied in the laboratory. From the foregoing, it can be concluded with the following remarks;

(i) The compressive strength of the treated soils improved consistently with increased proportion of GPC. And the results showed that with further addition of the geopolymer cement beyond the 120% mark used in this study, the properties would further be improved.
(ii) The erodibility potential of the treated soils also improved remarkably upon the addition of the additives to the proportion of 150% by weight of dry soil.
(iii) The durability potential also improved substantially in nondurable natural untreated soils with the addition of the synthesized additive.
(iv) Generally, the GPC has shown its potential to be used under hydraulically bound structures to improve the properties of expansive soil. Wet and dry cycles are very unfavorable conditions which expansive soils are exposed to; however, the GPC has shown that it can be used to resist the adverse effect of this phenomenon on foundations.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability The data supporting the results of this study is reported in the manuscript.

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