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Chinese Society of Pavement Engineering

International Journal of Pavement Research and Technology 11 (2018) 759-765

http://www.ijprt.org.tw/

Capillary rise, suction (absorption) and the strength development of HBM treated with QD base geopolymer

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Received 7 March 2018; received in revised form 18 April 2018; accepted 19 April 2018

Abstract

Test soil sample was investigated and characterized under the laboratory conditions with the preliminary tests. It was classified as A-2-6 group soil according to the AASHTO classification method. It was also classified according to USCS as poorly graded (GP) with high clay content (CH). It was also classified as highly plastic with plasticity index above 17% and expansive. The soil sample was further treated with synthesized Quarry dust (QD) base Geopolymer cement (GPC) at room temperature and the effects of the varying proportions of the GPC added in the proportions of 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5%, 20%, 22.5%, 25%, 27.5%, 30%, 32.5%, 35%, 37.5% and 40% by weight of solid on the cemented and non-cemented test soils under varying curing times on the soil capillary rise, suction and strength development parameters (UCS, CBR and MRD) were investigated. The results obtained showed a consistent reduction in capillary rise and suction with increased proportion of QD base GPC and an increase in these properties with increased curing time. But cemented soil showed a slight higher reduction in capillary rise and suction than the non-cemented soil, but at 15% QDbGPC all the trials have capillary rise below 25%. The strength development consistently improved with increased proportion of QDbGPC, that at 12.5% GPC, the trials achieved CBR above 30%, a minimum required for a material to be used as base course material and reduced with prolonged curing time due to loss of strength on prolonged water absorption. Portland cement has high shrinkage, and less capillary and absorption tendencies, though it showed lesser values of capillary rise and suction but the difference between cemented and non-cemented soils is too small that QD base GPC can totally replace OPC because of the construction properties it exhibits. It also shows that QD base GPC beyond 40% by weight will keep improving the strength of treated soils and achieve higher compressive strengths.

Keywords: Capillary rise; Modulus of Resilient Deformation; Strength development; Hydraulically bound materials; Quarry dust; Geopolymer

1. Introduction

Hydraulically bound materials (HBMs) are natural or synthetic; geopolymeric materials used in civil engineering works, which are subjected to moisture exposure throughout the life span of the infrastructure like the substructures or hydraulic structures e.g., dams, pools, ponds, retaining and gravity walls, and all subgrade layer of pavements; rigid or flexible. During this state of exposure, the strength properties and consequently the durability of the foundation materials; natural or treated are affected by physical factors for instance capillary rise, suction or absorption, erodibility, etc. [19]. Geopolymer cements (GPCs) have been studied and discovered to possess properties that could counterbalance the effects of exposure to these critical factors, which include acids, extreme

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Peer review under responsibility of Chinese Society of Pavement Engineering.

https://doi.org/10.1016/j.ijprt.2018.04.003
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temperatures above 600 °C, salts, fire, heavy metals, and more importantly and more relevant to this research work is its property of withstanding exposure to moisture attack in a hydraulically bound medium a factor dependent on the moisture sensitivity of GPCs [7]. In the present research, GPC was synthesized from highly aluminosilicate bound materials under alkali-activator medium of $NaOH + Na_2SiO_3$. These materials rich in aluminosilicates are fly ash (FA), ground granulated blast furnace or metallurgical slag (GGBFS). Quarry dust (QD) was characterized and was discovered to possess great amount aluminosilicates. This is a solid waste obtained from rock quarrying operation and its applications in the stabilization of soils have proven to improve the physico-mechanical properties of treated soil. Quarry dust (QD) is an amorphous waste product of rock quarry operation of highly aluminosilicate content [8]. This inorganic composition gives it the highly pozzolanic properties it possesses [2,14]. 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 [14]. In the present work, it is used as 50% replacement for FA in the synthesis of QD base GPC which was used to treat the test soil in the proportions of 2.5%, 5%, 7.5%, 10%, ..., 40% by weight of the treated matrix. It is also important to note that the constituents of the GPC possess high pozzolanic properties [2]. However the synthesized product possessed cementing properties. GP cements, binders and concretes have found a wide application in the infrastructure development industry and exhibits a great use in solid waste management, construction repair as geopolymer injection, toxic metal immobilization and coatings [11,4,10,12,5]. The application of blended QD 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 GP cement addition on capillary rise of cemented and non-cemented lateritic soils, (ii) to also study the effect of QD base GPC on the suction potential of the treated soils, and (iii) to study the effect of QD base GPC on the strength development of the treated soil.

2. Materials selection and experimental programme

2.1. Materials selection and preparation

The test soil sample was collected from Amaba borrow pit on Latitude 05°26′44.288″N and Longitude 07° 32′33.229″E. The disturbed sample was collected, tapped to remove lumps, sun dried for 3 days and readied for use. Quarry dust was collected as waste (byproducts) of quarrying (crushed-rock) operation from Amasiri quarry site in Afikpo, Ebonyi State, Nigeria. It was sundried and stored in silo bags for the laboratory exercise. Dangote Ordinary Portland Cement (DOPC) was bought at Umuahia Timber market, Umuahia, Nigeria. Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS)/Metallurgical Slag (MS) were collected from NigerPet Structures, Uyo, Nigeria and Delta Steel Company, Aladja, Warri, Nigeria respectively. The QD based Geopolymer (GP) was synthesized in accordance with the findings of Davidovits, Nikolov et al., Abdel-Gawwad and Abo-El-Enein, Hamidi et al., [11] Akbari et al., Skvara et al. and Srinivasan and Sivakumar [7,14], Abdel-Gawwad and Abo-El-Enein, 2016, [11,1,20,21]. According to the above research findings, the aluminosilicate materials needed in the formation of GP are FA and GGBFS or MS under the reactive influence of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) as activators with a combined molar concentration of 12 as an eco-friendly material. QD contains high concentration of aluminosilicates (Al-O-Si), maintains a highly pozzolanic property and serves well in the synthesis of GP cement. These materials are mixed in the proportion of 12% by weight Activator plus 22% by weight QD plus 22% by weight FA plus 44% by weight GGBFS (MS). If the synthesis and use of GP cement can replace the need for OPC, the atmosphere must have been set free of the effect of releasing an equivalent tonne of CO_2 emission into the atmosphere when cement is produced under higher energy consumptions. The atmosphere will eventually be set free of the waste or byproducts of biomass renewable energy plants; FA [18,15,16,17], byproducts of metallurgical operations; GGBFS (MS), and the byproducts of rock quarrying operations; QD by the application in the synthesis of GP cements and binders. The GP cement dry powder was stored for use as supplementary cementing material in the laboratory stabilization exercise.

2.2. Experimental programme

The following conventional tests were conducted on the natural test soil for the purpose of characterization and classification; Sieve Analysis Test: this was conducted with vertically arranged sieves mounted on an automatic shaker in accordance with BS 1377-2 and Nigerian General Specification [6], NGS, 1997, Compaction Test (Standard Proctor Test): this was conducted with 2016 ELE Automatic Compactor Machine in accordance with BS 1924 [6], and Nigerian General Specification [5,6], NGS, 1997, California Bearing Ratio Test (CBR): conducted with a 2015 S211 KIT CBR penetration machine, motorized 50 kN ASTM used to load the penetration piston into the soil sample at a constant rate of 1.27 mm/min (1 mm/min to BS Spec.) and to measure the applied loads and piston's penetrations at determined intervals in accordance with BS 1377-2, (BS 1924, 1990) and NGS [5,6], and NGS, 1997, Atterberg Limit Test: was conducted using a 2013 cassagrande apparatus in accordance with BS 1377-2, BS 1924 and NGS [5,6], NGS, 1997, Specific Gravity Test was conducted by Pycnometer method in accordance with BS 1377-2 and NGS [5] and NGS, 1997, and Chemical Oxides Composition Test on the test soils and the test materials with XRF method in accordance with BS 1377-2 and NGS [5] and NGS, 1997 and results were obtained. Furthermore, capillary rise and suction cylindrical specimens were prepared from the geopolymer treated cemented soil in accordance to the standard proctor mould geometry, which were compacted in three layers and cured for 14 days under the same laboratory conditions as the unconfined compressive strength specimens. Extra specimens were prepared for each mixture to ensure accuracy and forestall time loss due to accidents. The tests were conducted in accordance with the British Standard [6], NGS, 1997. After initial curing, the prepared specimens were dried to steady mass at a temperature of 60 °C ± 5 °C. Then, the height, mass and UCS of the specimens were measured as the control and standard reference values. The specimens were finally placed in a curing bowl with water level maintained at 10 mm and at room temperature of 26.8 °C ± 2 °C. The mean heights of water rising up the specimens were measured from the base of the sample specimens and equally their masses and UCS were determined at 24 h, 48 h and 72 h curing periods. Capillary rise as the percentage of the specimen height was determined and suction or absorption was calculated as the percentage of the specimens' dry masses and strength gain as a percentage of the initial UCS was estimated [5,6], NGS, 1997. A confined loading triaxial apparatus, which consists of an ordinary triaxial compression machine and a regulating device for axial stress, was used to determine the deformation of the treated soil compacted at the optimum moisture content and the deformation of the treated specimens was measured with a dial indicator of 1/100-mm gradations [5,6], NGS, 1997.

3. Results and discussion

3.1. Preliminary remarks

The test soil sample was investigated and characterized under the laboratory conditions with the preliminary tests as presented in Tables 1 and Fig. 1. The test soil was classified as A-2-6 group according to the AASHTO classification method (AASHTO, 1993). It was also classified according to USCS as poorly graded sand (GP) with high clay content (CH, SP-SC). It was also classified as highly plastic soil with plasticity index above 17% and expansive but with stiff consistency (UCS lies between 100 and 200 kN/m^2) at 7 and 28 days of curing [10]. Table 2 presents that the test materials have a high aluminosilicate content and possess pozzolanic properties [2].

3.2. Effect of GPC proportion on the capillary rise of the treated soil under varying curing times

The effect of varying proportions of QDbGPC by weight of treated sample on the capillary rise of the treated soil expressed as the percentage of the original height of the treated sample under varying curing times on both cemented and non-cemented soil is presented in Fig. 2. It was observed that increased proportion of QDbGPC brought about a reduced capillary rise on both cemented and non-cemented treated test soil and at 15% by weight QDbGPC, the whole trial tests at 24, 48, and 72 h curing had fallen below the minimum allowable critical line of 25% capillary rise suggested by Austroads, above which a hydraulically bound material remains unsafe [3]. On the other hand, capillary rise increased consistently at prolonged curing times on both cemented and non-cemented treated soils. The reduced capillary rise is due to that the higher content of sodium silicate activator tends to increase the release of Ca^{2+}, Si^{4+} and Al^{3+} from the metallurgical slag grains which eventually speed up geopolymerization reaction rate. 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. And 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 soil matrixes reducing capillary rise. Secondly this behaviour might be due to the GPC acting as fillers to reduce the porosity of the treated soil thereby reducing capillary rise. However, the increased capillary rise as a result of prolonged curing time or water exposure time could be due to the mobility of sodium and calcium ions at increased hours of curing which led to higher rate of geopolymerization thereby creating increased rise in moisture (Abdel-Gawwad and Abo-El-Enein, 2016). However, further increase in curing time increases the porosity of cemented matrix with a consequent increase in capillary rise values (Abdel-Gawwad and Abo-El-Enein, 2016). It can be observed that QDbGPC can totally replace OPC beyond 15% by weight for the fact that the capillary rise of the QDbGPC treated non-cemented soil fell below the allowable critical 25% line suggested by Austroads, making the QDbGPC a good replacement for OPC on treated HBM. And since prolonged curing affects the capillary rise of treated HBMs, a cemented test soil is prone to high

Table 1
Geotechnical properties of the test soil.

Test soil properties/unit		Test Results
% Passing BS No. 200 sieve		5.40
Natural Moisture Content, (%)		13
Liquid Limit, (%)		40
Plastic Limit, (%)		18
Plasticity Index, (%)		22
Coefficient of Curvature, $C_c = \frac{D_{30}^2}{D_{10}xD_{60}}$		4.54
Coefficient of Uniformity, $C_u = \frac{D_{60}}{D_{10}}$		4.23
Specific Gravity		2.6
AASHTO/USCS		A-2-6/GP/CH
Optimum Moisture Content, (%)		16.2
Maximum Dry Density (g/cm^3)		1.83
California bearing ratio, (%)		8
Unconfined Compression Strength (kN/m^2)	14 days	185
	7 days	142
Colour		Reddish Brown

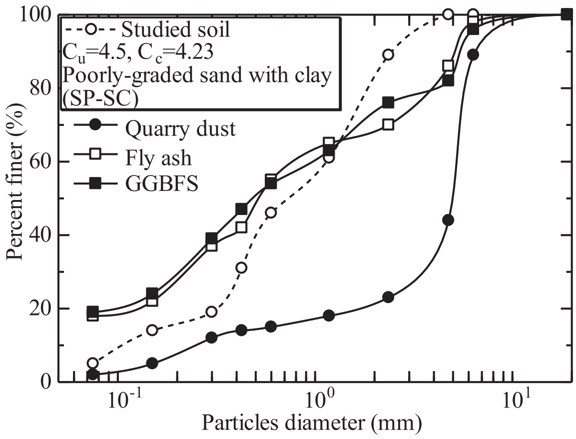

Fig. 1. Grain size distributions of studied materials.

tendency for shrinkage, cracking, brittle and consequently will be affected by capillary rise which may tend to cause the deterioration of the cemented HBM during a prolonged exposure to a moisture medium for instance the subgrade of pavements is exposed to capillary effects and the use of OPC during the construction should be avoided. This could be replaced with QDbGPC for a more capillary, brittle and shrinkage resistant structure.

3.3. Effect of GPC proportion on the suction of the treated soil under varying curing times

The effect of varying proportions of QDbGPC by weight of treated sample on the suction of the treated soil expressed as the percentage of the original mass of the treated sample under varying curing times on both cemented and non-cemented soil is presented in Fig. 3. It was observed that increased proportion of QDbGPC brought about a reduced suction on both cemented and non-cemented treated test soil and at the same time at a prolonged curing time, suction equally reduced. The consistently reduced suction with the increase in QDbGPC proportion may be due to the GPC acting as fillers to reduce the porosity of the treated soil thereby reducing suction. The reduction in porosity reduced the quantity of cementitious products occupying the matrix voids eventually reducing suction. At increased QDbGPC, the treated soil achieved a more densified microstructure which does not allow the absorption of moisture due to the flocculation and agglomeration of the treated soil particles. Hydration reaction of a GPC takes place at room temperature within 24 h letting the material at high degrees of suction within which it gains its maximum strength and used up the highest amount of moisture need for this process. This showed that if water is used as pore fluid, the influence of the mechanical factors would remain the same (Meegoda and Rantanweera, 1994). During this procedural exercise, the rate of suction decreased as the water content of the treated matrix increased even at increased water exposure time. So at prolonged curing beyond 24 h, the rate of moisture intake is reduced drastically hence the behaviour that was observed.

3.4. Effect of GPC proportion on the strength development (UCS) of the treated soil under varying curing times

The effect of varying proportions of QDbGPC by weight of treated sample on the strength development (UCS) of the treated soil expressed as the percentage of the original UCS of the treated sample under varying curing times on both cemented and non-cemented soil is presented in Fig. 4. It was observed that increased proportion of QDbGPC brought about an improved UCS index on both cemented and non-cemented treated test soil but at the prolonged curing time or water exposure time, UCS index

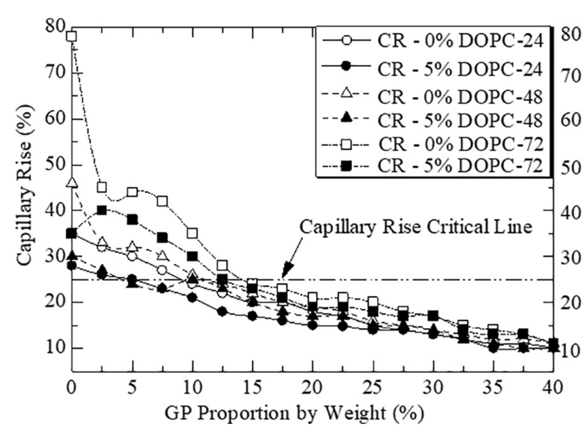

Fig. 2. Effect of geopolymer addition on the capillary rise at different curing times on the treated soil.

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
Test Soil	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	–	–	–	–0.03
FA	63.45	4.14	12.1	1.23	0.78	1.09	0.01	1.78	1.89	0.71	0.11	–	0.40
GGBFS	33.45	12.34	142.10	0.05	11.45	–	–	–	0.21	–	–	–	
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.

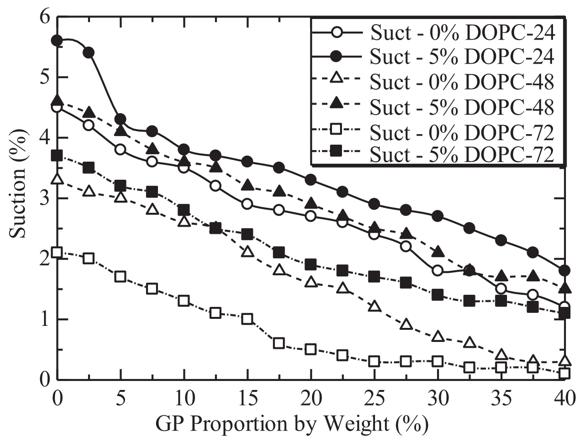

Fig. 3. Effect of geopolymer addition on the capillary rise at different curing times on the treated soil.

reduced. It is important to note that this behaviour may be due to the increase release of Ca^{2+}, 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 and the consequent strength gain [13], Osinubi, 2000, Gidigasu and Dogbey, 1980, [19]. This confirms the fact that higher proportions of QDbGPC may encourage the use of little or no Portland cement reducing cost, brittle, cracking and shrinkage potential. Secondly, the increased proportions of QD base GPC may have caused a consistent strength gain in the treated matrix because the GPC may have filled the voids within the soil mass during the stabilization procedure to improve the porosity of the treated soils and because of its pozzolanic properties, which enhanced calcinations reaction, pozzolanic reaction, and the inclusion of Na_2SiO_3 in NaOH solution provides higher silicate concentration and gave 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 [13], Osinubi, 2000, Gidigasu and Dogbey, 1980, [19]. 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. And 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 soil matrixes. The presence of GGBFS provided room temperature hardening and increased the mechanical strength by proving Ca^{2+} responsible for this effect [7].

The results presented in Fig. 5 show that the CBR of the treated soil improved considerably and with remarkable increase with increase in QDbGPC and a slight and consistent increase CBR with increase in DOPC was observed. This was due to the excess calcium ion made available for hydration reaction, flocculation, densification and polycondensation by the GGBFS as well as the pozzolanic effect of the high aluminosilicate content in QD. This may also be due to the excess presence of the same calcium from the GPC adequate enough for the formation of calcium silicates hydrate and calcium aluminate hydrate, which are the major complex compounds responsible for strength development. It is remarkable to observe that at 12.5% addition of QDbGPC, the treated soil at 0%, 1%, 2%, 3%, 4% and 5% DOPC met the minimum CBR value requirements of 30% specified by British Standard Institute [6] for materials suitable for use as base course material in pavement construction. This is also close to the findings of Gidigasu and Dogbey [9], which stated that a minimum CBR value of 20–30% is required for subbases when compacted at optimum moisture.

Effect of GPC variation on Modulus of Resilient Deformation is also presented in Fig. 6. It is important to note that when the confining pressure is high the resilient deformation (%) usually decreases and the Modulus of Resilient Deformation improves as a result of the apparent hardening behaviour of the treated specimens. This potential behaviour or property is more observed when the intensity of repeated and varied stress is low but the present

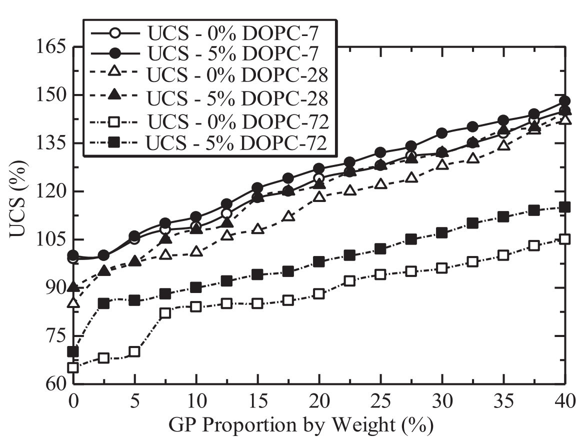

Fig. 4. Effect of geopolymer addition on the UCS at different curing times on the treated Soil.

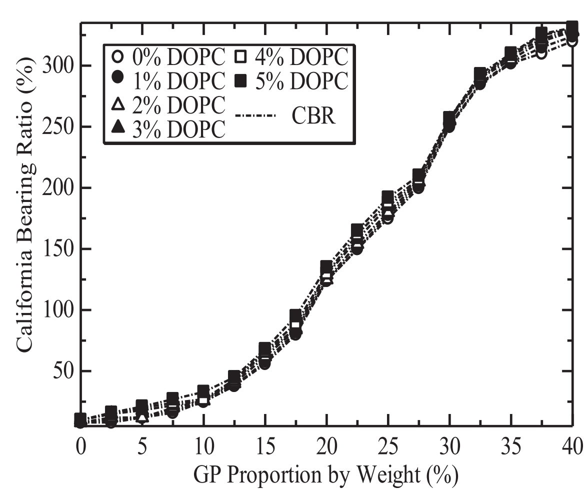

Fig. 5. Effect of geopolymer variation on the California Bearing Ratio (CBR).

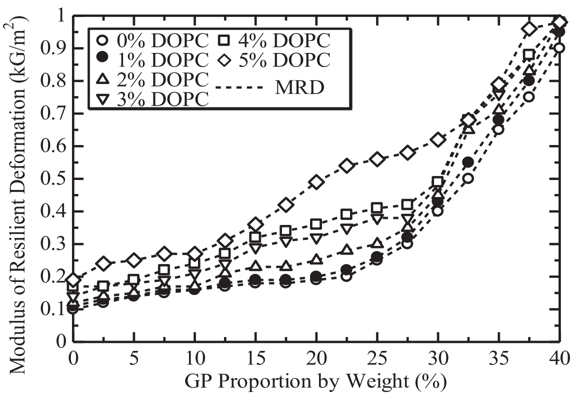

Fig. 6. Effect of geopolymer variation on the Modulus of Resilient Deformation (MRD).

situation is presented for a constant confining stress. Also, when treated specimens of sandy soil or soil of high water content are subjected to increased confining pressures the hardening and strengthening response or behaviour is more apparent, and the resilient deformation decreases and the MRD increases (Fig. 6). The treated specimens of clayey soil in the present case exhibit less hardening effect and their MRD varies little with variation in the DOPC content compared to the variation in GPC content. This is due to the fact the GPC has proven to produce more hardening compounds at the ionic state responsible to the strength gain index effect observed with increased GPC. For all the proportions of GPC, the MRD increased consistently.

4. Concluding remarks

Taking into consideration the results of the laboratory exercises conducted on the QD base GPC treated soil, it can be concluded with the following remarks:

(a) The test soil was tested for the basic properties and results show that it was classified according to AASHTO classification system and USCS as A-2-6 and GP groups respectively; it was also classified as a highly plastic soil with plasticity index above 17% and expansive.

(b) The QD base GPC synthesized in accordance with the conditions suggested by previous research findings [7], was used to treat the test soil under the laboratory conditions and was added in the proportions of 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5%, 20%, 22.5%, 25%, 27.5%, 30%, 32.5%, 35%, 37.5% and 40% and under varying water exposure times to determine the capillary and suction behaviour and strength development behaviour of the treated soils.

(c) The alkali-activated ($NaOH + Na_2SiO_3$) cement produced under dry condition provided the possibility to adapt waste inorganic materials and the properties of such cements are always better than those of ordinary Portland cement (OPC). The concentration of NaOH was kept lower than the concentration of Na_2SiO_3 to check the excessive release of OH^- which may have led to inefficient geopolymerization reaction.

(d) Results from the above procedure showed that the QD base GPC treated soils demonstrated significant and consistent reduced capillary rise and suction and more importantly, the strength improvement; UCS, CBR and MRD with increased QD base GPC proportion by weight. More important to note is the remarkable strength improvement recorded at 0% DOPC. This showed that the properties of GPC may be fully utilized in the stabilization protocol to achieve a hydraulically bound stabilized material that possesses high compressive strength, high temperature resistance of above 600 °C, resistant to acid, salts and sulphte attacks, and resistant to brittle and corrosion effects. This behaviour may be attributed to the properties of the constituent elements of the GPC where GGBFS produces high levels of calcium and QD produces high concentration of aluminosilicates, which contribute to strength gain by calcinations, cation exchange, hydration reactions and polycondensation.

Acknowledgement

The efforts of the technologist of Fugro Nigeria Limited are acknowledged and as well as the financial assistance from Dr. Duc Bui Van and Dr. Manh Nguyen Van.

References

[1] H. Akbari, R. Mensah-Biney, J. Simms, Production of geopolymer binder from coal fly ash to make cement-less concrete, World of Coal Ash (WOCA) Conference in Nashville, TN, 2015, May 5–7 [online].
[2] American Standard for Testing and Materials ASTM C618, Standard Specification for Pozzolan, ASTM, West Conshohocken, 2014, www.astm.org.
[3] Austroads, Mix Design for Stabilized Pavement Materials, Austroads Publication AP-T16, Sydney, 2002.
[4] L. Bromley, D. Hadfield, Geotechnical Asset Management: How Structural Engineers can Exploit Geo-polymer Injection Technology. URETEK Technical Report, 2017 [online].
[5] BS 1377-2, Methods of Testing Soils for Civil Engineering Purposes, British Standard Institute, London, 1990.
[6] BS 1924, Methods of Tests for Stabilized Soil, British Standard Institute, London, 1990.
[7] J. Davidovits, Geopolymer Cement a Review, Institute Geopolymer, F-02100 Saint-Quentin, France, 2013 [online].
[8] W. Fedrigo, W.P. Nunez, T.R. Kleinert, M.F. Matuella, J.A.P. Ceratti, Strength, shrinkage, erodibility and capillary flow characteristics of cement-treated recycled pavement materials, Int. J. Pavement Res. Technol. 10 (2017) 393–402, https://doi.org/10.1016/j.ijprt.2017.06.001.
[9] M.D. Gidigasu, J.L.K. Dogbey, Geotechnical Characterization of Laterized Decomposed Rocks for Pavement Construction in Dry Sub-humid Environment, 6th South East Asian Conference on Soil Engineering, Taipei, 1980, pp. 493–506.
[10] R. Gopal, A.S.R. Rao, Basic and applied soil mechanics, third ed., New Age Int'l Publishers, New Delhi, 2011.

[11] R.M. Hamidi, Z. Man, K.A. Azizli, Concentration of NaOH and the effect on the properties of fly ash based geopolymer, in: 4th International Conference of Process Engineering and Advanced Materials, Procedia Engineering, 2016, pp. 189–193, https://doi.org/10.1016/j.proeng.2016.06.568.
[12] R. Laila, B. James, A. Rouhollah, M. Jon, TS,, Review of cement and concrete nanoscience and nanotechnology, Materials 3 (2010) 918–942.
[13] N.J. Meegoda, P. Ratanweera, Compressibility of contaminated fine grained soil, Geotech. Test. J. ASTM 17 (1994) 101–112.
[14] A. Nikolov, I. Rostovsky, Nugteren Henk, Geopolymer materials based on natural zeolite, Case Stud. Constr. Mater. 6 (2017) 198–205, https://doi.org/10.1016/j.cscm.2017.03.001.
[15] K.C. Onyelowe, Renewable energy by-products (REB) adaptation successes in environmental geotechnics: a review, J. Fundam. Renewable Energy Appl. 7 (2017) 239, https://doi.org/10.4172/20904541.1000239 [online].
[16] K.C. Onyelowe, Nanostructured waste paper ash treated lateritic soil and its California bearing ratio optimization, Glob. J. Technol. Optim. 8 (2017) 220, https://doi.org/10.4172/2229-8711.1000220 [online].
[17] K.C. Onyelowe, Nanostructured waste paper ash stabilization of lateritic soils for pavement base construction purposes, Electron. J. Geotech. Eng. 22 (09) (2017) 3633–3647.
[18] K.C. Onyelowe, Nanosized palm bunch ash stabilization of lateritic soils for construction purposes, Int. J. Geotech. Eng. (2017), https://doiorg/10.1080/19386362.2017.1322797 [Online].
[19] K.C. Onyelowe, B.V. Duc, Durability of nanostructured biomasses ash (NBA) stabilized expansive soils for pavement foundation, Int. J. Geotech. Eng. (2018), https://doiorg/10.1080/19386362.2017.1422909 [Online].
[20] F. Skvara, T. Jilek, L. Kopecky, Geopolymer materials based on fly ash, Ceram. Silik. 46 (3) (2005) 195–204.
[21] K. Srinivasan, A. Sivakumar, Geopolymer binders: a need for future concrete construction, ISRN Polym. Sci. 2013 (2013), https://doi.org/10.1155/2013/509185.