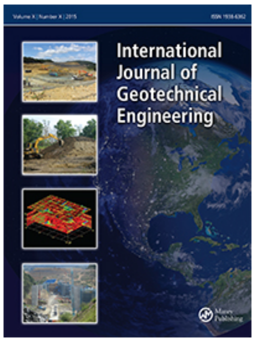

International Journal of Geotechnical Engineering

ISSN: 1938-6362 (Print) 1939-7879 (Online) Journal homepage: http://www.tandfonline.com/loi/yjge20

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To cite this article: Kennedy Chibuzor Onyelowe, Duc Bui Van & Manh Nguyen Van (2018): Swelling potential, shrinkage and durability of cemented and uncemented lateritic soils treated with CWC base geopolymer, International Journal of Geotechnical Engineering, DOI: 10.1080/19386362.2018.1462606

To link to this article: https://doi.org/10.1080/19386362.2018.1462606

INTERNATIONAL JOURNAL OF GEOTECHNICAL ENGINEERING, 2018
https://doi.org/10.1080/19386362.2018.1462606

Swelling potential, shrinkage and durability of cemented and uncemented lateritic soils treated with CWC base geopolymer

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ABSTRACT

The swelling potential, shrinkage limits, strength development and durability of crushed waste ceramic base geopolymer cement (CWCbGPC) treated test soils A, B and C have been studied under the laboratory conditions. The test soil samples were preliminarily investigated and characterized under the laboratory conditions. Soils A, B and C were classified as A-2-7, A-2-6 and A-7, respectively, according to the AASHTO classification method. They were also classified according to USCS as poorly graded. Additionally, soils A and C were observed as having higher clay content than soil B. They were also classified as highly plastic with plasticity index above 17% and expansive. The free swell index and shrinkage tests showed that they had high potential for swelling and shrinkage. The treated soils show significant improvement in swelling, shrinkage, strength development and durability with CWCbGPC while the cemented soils failed in terms of shrinkage and durability, which proved that Portland cements have high potential for shrinkage with soil blends. The results of the laboratory study have shown that CWCbGPC and other geopolymer cements can totally replace Portland cements in civil engineering works more especially in the construction of hydraulically bound structures.

ARTICLE HISTORY
Received 24 February 2018
Accepted 3 April 2018

KEYWORDS
Durability; swelling and shrinkage; compacted lateritic soils; quarry dust; metallurgical slag; crushed waste ceramics; geopolymer

Highlights

- CWC base GPC was synthesized in accordance with research findings
- Test soil sample was studied to determine the preliminary properties
- The test materials were studied and characterized to determine their aluminosilicate content
- The CWC base GPC was applied in the stabilization of test soil
- The effect of CWC base GPC on swelling of the treated soil was studied
- The effect of CWC base GPC on shrinkage of the treated soil was studied
- The effect of CWC base GPC on durability of the treated soil was studied

1. Introduction

Crushed Waste Ceramic is a solid waste resulting from scrap loss of industrial production process, used ceramic plates or tiles and from handling centres, blended and recycled for reuse as a geosynthetic material. Because of the materials' high aluminosilicates and pozzolanic content, it has found its reuse in the stabilization of earth materials adapted in contruction. Today's infrastructural construction ranging from hydraulic structures, pavements, sub-structures, etc. are exposed to variations in moisture and are known as hydraulically bound structures. Hydraulically bound materials (HBM) 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 sugrade and subbase layers 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, swelling, shrinkage, erodibility, strength development, etc. (Onyelowe and Van Bui 2018a, 2018b). Geopolymer cements (GPC) have been studied and discovered to possess properties that could counterbalance the effects of exposure to these critical factors, which include acids, extreme 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 (Davidovits 2013), which eventually counts on the durability of the structures. 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

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quarry dust (QD), metallurgical slag (MS). QD was characterized and was discovered to possess great amount aluminosilicates. This is 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. QD is an amorphous waste product of rock quarry operation of highly aliminosilicate content (Fedrigo et al. 2017). This inorganic composition gives it the highly pozzolanic properties it possesses (ASTM C618 2014; Nikolov, Rostovsky, and Henk 2017). Geopolymers on the same hand are produced from amorphous materials of highly auminosilicate 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, Rostovsky, and Henk 2017). In the present work, it is used as 50% replacement for FA in the synthesis of crushed waste ceramics (CWC) base GPC which was used to treat the test soil in the proportions of 5, 10, 15, 30, …, 60% by weight of the treated matrix. It is also important to note that the constituents of the GPC possess high pozzolanic properties (ASTM C618 2014). However, the synthesized product possessed cementing properties. GP cements, binders and concretes have found wide application in the infrastructures development industry and exhibits great use in solid waste management, construction and pavement foundation repair as geopolymer injection, toxic metal immobilization and coatings (BS 1377-2 1990; Laila et al. 2010; Gopal and Rao 2011; Hamidi, Man, and Azizli 2016; Bromley and Hadfield 2017). The application of blended CWC base geopolymer for the treatment of compacted soils was investigated in the present work. However in this work, the preliminary properties of test soils and their behaviour with crushed waste ceramic base geopolymer cement (CWCbGPC) treatment were studied with particular emphasis on; (i) the effect of GP cement addition on swelling potential of cemented and non-cemented lateritic soils, (ii) the effect of CWC base GPC on the drying shrinkage of the treated soils, and (iii) the effect of CWC base GPC on the strength development and durability of the treated soil.

2. Materials preparation and methods

2.1. Materials preparation

The test soil samples were collected from Olokoro, Amaba and Ohia borrow pits. The test soils location maps are presented in Figure 1. The disturbed samples were collected, tapped to remove lumps, sun dried for 3 days and readied for use. CWC was collected as waste from ceramic depots sale outfits and companies. It was sun-dried, blended and stored in silo bags for the laboratory exercise. Dangote ordinary Portland cement (DOPC) was bought at Umuahia Timber market, Umuahia, Nigeria. QD was collected from rock quarry site, Amasiri, Afikpo, Ebonyi State. MS was collected from Delta Steel Company, Aladja, Warri, Nigeria. The CWC based Geopolymer (GP) was synthesized in accordance with the findings of Davidovits, Nikolov et al., Abdel-Gawwad and Abo-El-Enein, Hamidi et al., Akbari et al., Skvara et al. and Srinivasan and Sivakumar (Skvara, Jilek, and Kopecky 2005; Xiao et al. 2005; Davidovits 2013; Srinivasan and Sivakumar 2013; Akbari, Mensah-Biney, and Simms 2015; Yang and Li 2015; Abdel-Gawwad and Abo-El-Enein 2016; Hamidi, Man, and Azizli 2016; Nikolov, Rostovsky, and Henk 2017). According to the above research findings, the aluminosilicate materials needed in the formation of GP are QD, MS and CWC under the reactive influence of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) as activators of a combined eco-friendly molar concentration of 12 M. CWC contains high concentration of aluminosilicates (Al-O-Si), maintains a highly pozzolanic property and serves the binding purpose in the synthesis of GP cement. These materials are blended in the proportion of 12% by weight Activator plus 22% by weight CWC plus 22% by weight QD plus 44% by weight 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 solid waste or by-products of quarrying; QD (Onyelowe 2017a), by-products of metallurgical operations; MS, and the industrial solid waste; CWC by their application in the synthesis of GP cements and binders. The GP cement dry powder was stored for use and study as supplementary cementing material and total replacement for DOPC in the laboratory stabilization exercise.

2.2. Experimental programme

The following conventional tests were conducted on the natural test soils for the purpose of characterization and classification; Sieve Analysis Test: this was conducted with a vertically arranged sieve sizes mounted on an automatic shaker in accordance with BS 1377-2 and Nigerian General Specifiction (BS 1377-2 1990; NGS 1997), Compaction Test (Standard Proctor Test): this was conducted with 2016 ELE Automatic Compactor Machine in accordance with BS 1377-2, BS 1924 and NGS (BS 1377-2 1990; BS 1924 1990; NGS 1997), California Bearing Ratio Test (CBR): conducted with a 2015 S211 KIT CBR penetration machine, motorized 50kN 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 and NGS (BS 1377-2 1990; BS 1924 1990; NGS 1997), Atterberg Limit Test: was conducted using a 2013 Casagrande apparatus in accordance with BS 1377-2, BS 1924 and NGS (BS 1377-2 1990; BS 1924 1990; NGS (Nigeria General Specification/ Federal Ministry of Works and Housing) 1997), Specific Gravity Test was conducted by Pycnometer method in accordance with BS 1377-2, BS 1924 and NGS (BS 1377-2 1990; BS 1924 1990; 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 (BS 1377-2 1990; NGS 1997 and results were obtained. Furthermore, drying shrinkage cuboidal specimens (75 mm × 75 mm × 250 mm) were prepared from the geopolymer treated cemented and uncemented soils in accordance with AS 1012.13 (1992) which were compacted in three layers and cured for 24 h 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. In order to facilitate shrinkage measurements, gauge studs were installed in place at the centre of the ends cross sections at the compaction stage. After the 24 h curing, the treated and untreated (control) specimens were dried for 4, 8, 12, 16, 20

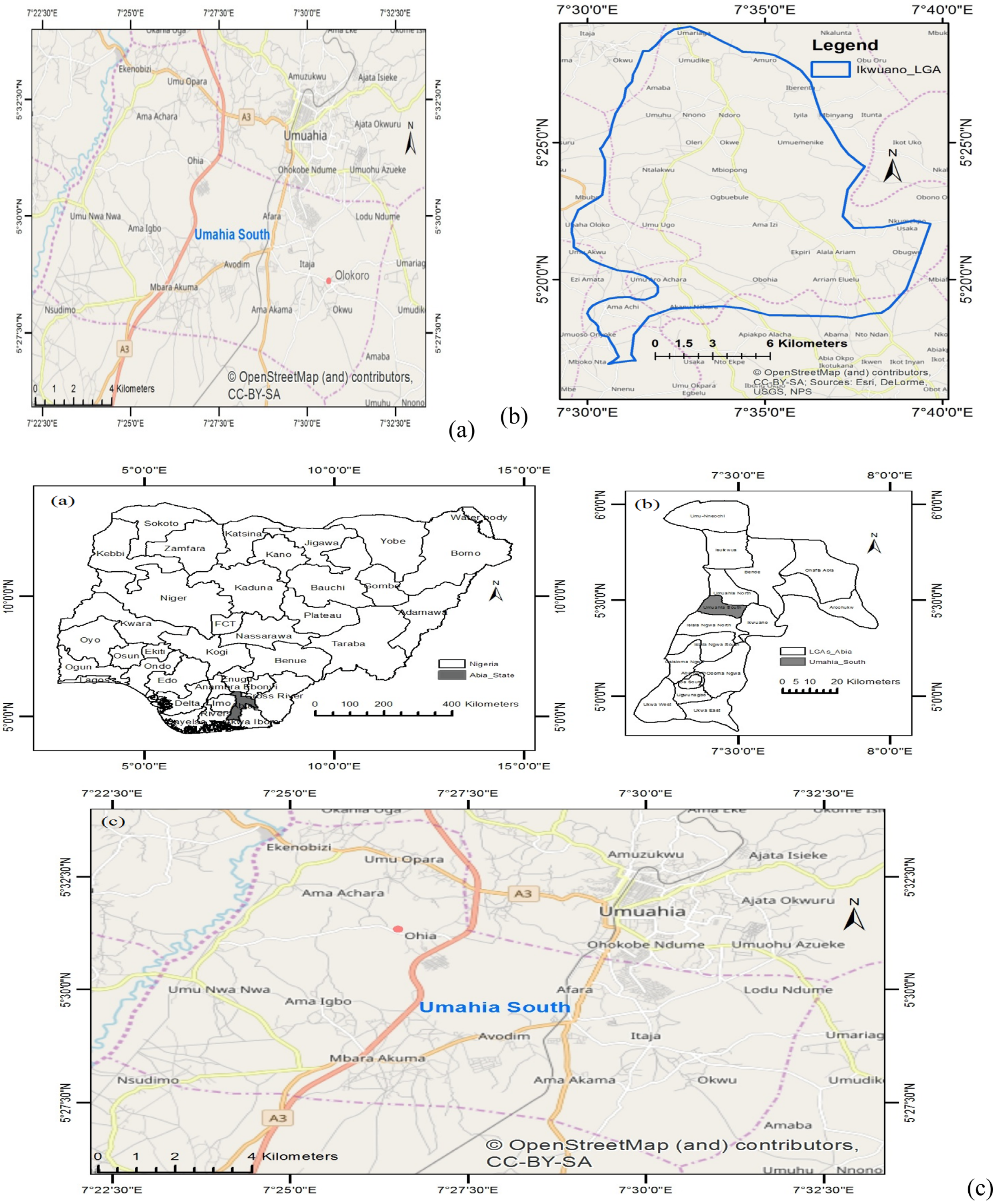

Figure 1. Olokoro, Amaba and Ohia test soils sample location maps.

and 24 h at room temperature. The length differences of the of the specimens were observed with a horizontal length comparator with a micrometer. For every round of drying period for the specimens, the length difference was measured and subtracted from its initial length and divided by the gauge length expressed as a percentage. The swelling test was conducted on the treated and untreated (Free Swell Test) soils in accordance with ASTM D4546-14 (ASTM D4546-14 2014). The CWCbGPC was varied between 5 and 60% in a steady increment of 5 and the treated soil specimens were cured for 3, 7, 14, 28, 36, 56 and 72 days to determine the swelling potential of the treated soils expressed as Equation (1). The loss of strength in immersion experiment was proposed in Series 800 (MCHW-V1, 2007) using the procedure given in Section 880.4. Two sets of test cylinders with a ratio of 1:1 (Diameter: Height) are prepared and air-cured for 14 days. While ‘Set A’ continued air-curing, ‘Set B’ of the test cylinders

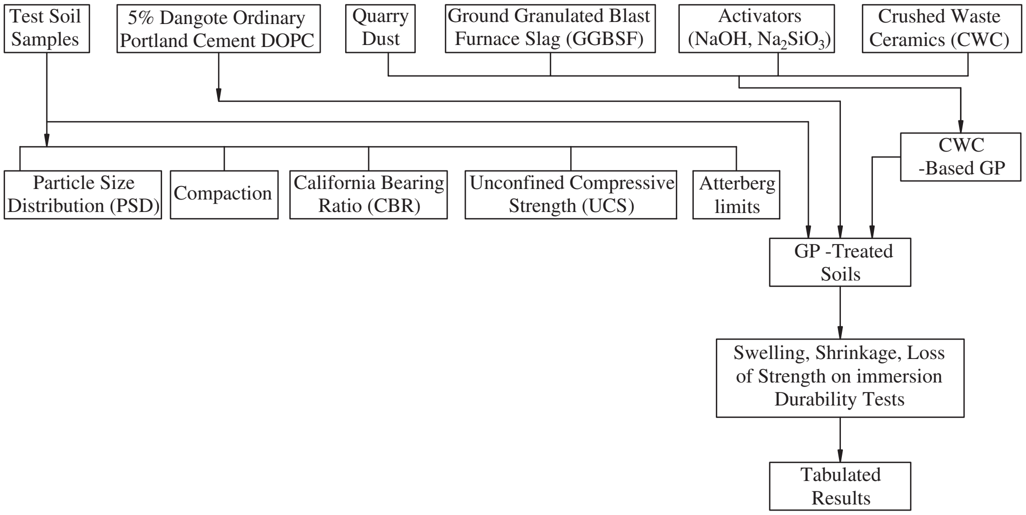

Figure 2. Schematic presentation of the experimental programme.

were then cured for a further 14 days completely immersed in water. The compressive strength of these immersed samples (UCS_{imm}) was determined together with that of the control specimens ($UCS_{control}$). The control specimens are cured for 28 days at room temperature. All curing is undertaken at room temperature for the materials assessed in this research work. The mixture is considered to be durable if the following applies expressed as Equation (2) (Manual of Contract Documents for Highway Works-V1 2007) (Figure 2):

$$S_p = \frac{\delta h}{h} x\, 100 \tag{1}$$

where S_p = swelling potential in per cent; δh = amount vertical swell; h = initial height

$$UCS_{VS}(I_D) = \frac{UCS_{imm}}{UCS_{control}}\; x\; \frac{100}{1} \geq 80\% \tag{2}$$

where UCS_{VS} = relative volumetric stability, which is assumed to be durable if ≥80%. I_D = durability index.

3. Results and discussion

3.1. General behaviour and classification of test materials

The results of the experimental programme have been presented in tables and graphs in the following pages. Test soil samples were investigated and characterized under the laboratory conditions with the preliminary test as shown in Tables 1 and 2 and Figure 3. Soils A, B and C were classified as A-2-7, A-2-6 and A-7 groups, respectively, according to the AASHTO classification method (AASHTO 1993). They were classified according to USCS as poorly graded (GP). Additionally, soils A and C were observed as having higher clay content than soil B and higher free swell index (FSI) while soils B and C have higher potential for shrinkage with a shrinkage limit (SL) of 7%. They were also classified as highly plastic with plasticity index above 17% and expansive. Table 3 presents that the test materials have high aluminosilicate content and possess pozzolanic properties (ASTM C618 2014). Table 3 shows the oxide rates and bonding potentials of the test materials, which satisfied that the material bonding is a very important factor in soil stabilization and strength development because the soil and the admixture need to form a homogeneous and cohesive bond (Rafat and Mohammad 2011). Material requirement for cementitious materials states that the sum of the oxide rates of SiO_2, Al_2O_3, and Fe_2O_3 should not be less than 70%. The results of the analysed materials presented in Table 3 show that the percentage of SiO_2 + FeO_3 + Al_2O_3 for each of the materials is greater than 70%,which makes the test material samples highly pozzolanic (Rafat and Mohammad 2011). This property was of great advantage because it brought about a high degree of interaction, pozzolanic reaction, carbonation reaction and bonding between the studied soils and the synthesized GPC (ASTM C618 2014).

Table 1. Basic properties of test soils.

Property description of test soils and units	Behaviour		
	Olokoro test soil (A)	Amaba test soil (B)	Ohia test soil (C)
% Passing Sieve No 200	2.85	10	4.6
NMC (%)	12.1	13.49	14
LL (%)	40	46	64
PL (%)	18	21	36
PI (%)	22	25	28
SL (%)	8	8	7
FSI (%)	250	234	275
G_S	2.6	2.43	2.12
AASHTO classification	A-2-7	A-2-6	A-7
UCSC	GP, CH	GP	GP, CH
MDD (g/cm³)	1.76	1.85	1.80
OMC (%)	13.1	16.2	13.13
CBR (%)	12	13	8
Colour	Reddish brown	Reddish grey	Reddish ash

3.2. Consistency behaviour of DOPC and CWCbGPC treated test soils

Tables 4–6, Figures 4–6 summarized the consistency behaviour of the treated, cemented and uncemented lateritic soils with the

Table 2. Particle size distribution (PSD) of test materials.

	% Passing sieve (mm)										
Materials	19	6.35	4.75	2.36	1.18	0.6	0.425	0.3	0.15	0.075	Pan
Soil A	–	100	89	67	59	44	36	22	15	2.85	0
Soil B	–	100	91	82	63	50	39	28	21	10	0
Soil C	–	–	100	89	61	46	31	19	14	5	0
Quarry dust	100	89	44	23	18	15	14	12	5	2	0
CWC	100	97	86	70	55	45	33	28	25	21	0
GGBFS	100	96	82	76	63	54	47	39	24	19	0

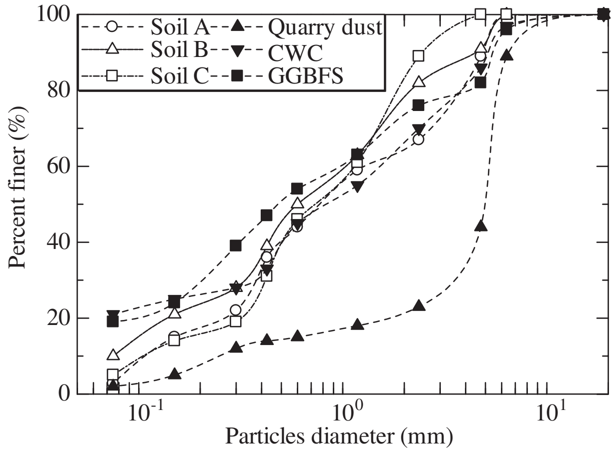

Figure 3. Particle size distribution of studied materials.

addition of different rates of CWCbGPC material. The natural soils had a highly plastic consistency of PI greater than 17%. But the behaviour reduced, obviously to 'medium plastic' consistency at the addition of the additive geopolymer material. At 5% DOPC to soils A, B and C, the PI reduced to 18, 21 and 25% respectively while beyond the addition of 20% CWCbGPC, the PI of the treated soils A and B reduced below 17% and beyond 25% CWCbGPC for soil C. This trend continued on further addition of the GPC. The hydration of the treated mixture and its increased calcium content from the MS has contributed to behaviour of the soil and also due to molecular rearrangement in the formation of transitional compounds. This improvement is due to the hydration of the highly aluminosilicate and pozzolanic additives with the treated mixture, which reduced the PI consistently thereby producing a stiff mixture of stabilized soil. Also, the release of cations from the geopolymer material constituents during the cation exchange reaction has contributed to the behaviour of the treated soils. This behaviour agrees with Meegoda and Ratanweera (1994), which showed that if water is used as pore fluid, the influence of the mechanical factors would remain same with a general decrease in LL on addition of an admixture. However, if an organic fluid other than water is used,

Table 3. Oxides composition of the materials used in this paper.

	Oxides composition (content wt %)											
Materials	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	–	–	–	–
CWC	64.45	24.14	0.25	1.3	0.28	3.69	2.51	0.18	1.09	–	2.11	–	–
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

Notes: IR is Insoluble Residue, LOI is Loss on Ignition, CWC: Crushed Waste Ceramics.
QD: Quarry dust, GGBFS: Ground granulated blast furnace slag.
DOPC: Dangote ordinary Portland cement.

Table 4. Consistency limits of CWCbGPC treated soil A.

			Consistency limits (%) of CWCbGPC % by weight treated soil A; A-2-7/GP/CH											
Test	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
w_L	40	38	39	37	36	35	32	31	29	29	29	28	27	25
w_p	18	20	19	18	18	18	16	17	17	19	22	24	23	21
I_p	22	18	20	19	18	17	16	14	12	10	7	4	4	4

Table 5. Consistency limits of CWCbGPC treated soil B.

			Consistency limits (%) of CWCbGPC % by weight treated soil B; A-2-6/GP											
Test	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
w_L	46	44	42	40	39	38	38	36	34	31	28	25	22	18
w_p	21	23	18	17	17	18	22	23	23	22	21	22	19	15
I_p	25	21	24	23	22	20	16	13	11	9	7	3	3	3

Table 6. Consistency limits of CWCbGPC treated soil C.

Test	Control	5% DOPC	Consistency limits (%) of CWCbGPC % by weight treated soil C; A-7/GP/CH											
			5	10	15	20	25	30	35	40	45	50	55	60
w_L	64	60	61	54	50	47	42	36	31	26	18	18	15	12
w_p	34	35	35	30	27	26	22	19	16	13	11	11	8	5
I_p	28	25	26	24	23	21	20	17	15	13	7	7	7	7

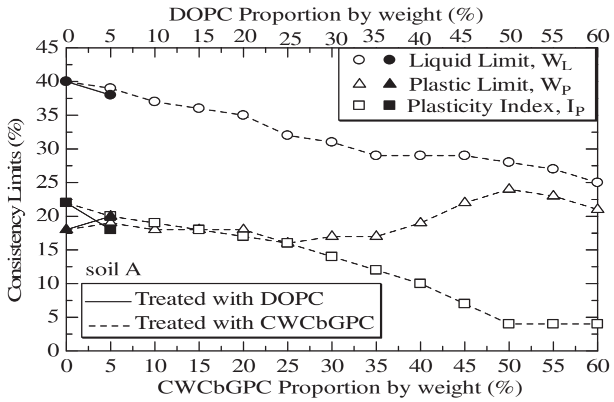

Figure 4. Consistency limits of treated soil A.

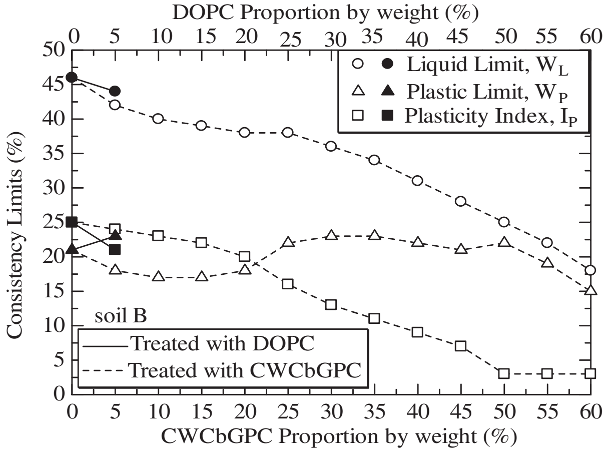

Figure 5. Consistency limits of treated soil B.

the physical properties of the fluid such as viscosity and density would influence the LL. With the varying behaviour with the addition of CWCbGPC, it can be seen that the LL depends on mechanical factors other than the pore fluid viscosity and density (Gidigasu and Dogbey 1980; Masaki and Eiji 2006; Onyelowe and Agunwamba 2012; Olawale 2013; Akbari, Mensah-Biney, and Simms 2015; Onyelowe and Okafor 2015; Bromley and Hadfield 2017; Nikolov, Rostovsky, and Henk 2017) and to a higher degree on the physicochemical properties of carbonation, cation exchange and polycondensation. Consequently, the use of the treated soils as subgrade and base materials has been improved by the presence of the CWCbGPC and achieved non-frost-susceptible materials with PI less than 15; a very important function affecting the durability of pavements and other civil engineering works founded on soil (Smith and Smith 1998; Gopal and Rao 2011). The achieved subgrade improvement will reduce the required pavement thickness; wearing course + base course, hence a cost effective and durable pavement construction as a hydraulically bound structure (Gidigasu and Dogbey 1980; Fwa 2006; Gopal and Rao 2011).

3.3. Compaction behaviour of DOPC and CWCbGPC treated test soils

The compaction behaviour of the CWCbGPC treated soils were observed to improve in terms of dry density and OMC as presented in Tables 7-9, Figures 7-9. There was an increase in the maximum dry density at 5% by weight addition of DOPC with a corresponding reduction in the OMC, while there was a consistent increase in MDD and associated decrease in OMC with the varied addition of the CWCbGPC. There was a possibility that the formation of new compounds occurred which consequently led to the increase in the MDD with addition of the CWCbGPC. This behaviour may also be due to cation exchange reactions, flocculation, polycondensation and the filling of the voids within the soil matrix thereby improving the porosity and in addition, the flocculation and agglomeration of the clay particles due to polarization, release and exchange of ions (Gidigasu and Dogbey 1980; Osinubi, Bafyau, and Eberemu 2009; Fedrigo et al. 2017). The trend is in conformity with the results reported by (Onyelowe 2017a). An explanation that was offered for this trend is that there was increasing desire for water, which commensurate with the higher amount of CWCbGPC because more water was required for the dissociation of constituents with Ca^{2+} and OH^- ions to supply more Ca^{2+} for the cation exchange reaction (Rafat and Mohammad 2011). The decrease in the OMC with increased proportions of CWCbGPC content might be due to cation exchange that also caused the flocculation of clay particles. Moreover, the GPC constituents or test materials are highly pozzolanic materials and require water for hydration thereby improving the strength gain and the durability of the treated soils.

3.4. Swelling potential of DOPC and CWCbGPC treated test soils

The vertical swell behaviour of the DOPC and CWCbGPC treated soils were presented in Tables 10–12, Figures 10–12 which represent soils A, B and C, respectively. Both control experiments, and the treated exercises showed a consistent increase in the swelling potential with the curing time. Conversely, the swelling potential decreased with increase in the addition of CWCbGPC. With soil A, it is observed that at 55 and 60% addition of CWCbGPC, the swelling potential reduced between 56 and 72 days of curing from 2.9 to 2.3% and between 3 and 7 days of curing time from

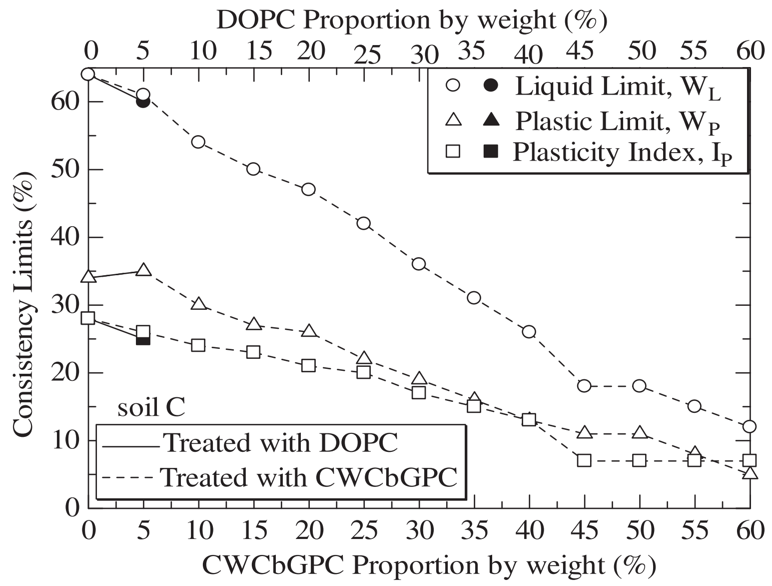

Figure 6. Consistency limits of treated soil C.

Table 7. Effect of CWCbGPC on the compaction of treated soil A.

			Compaction of CWCbGPC % by weight treated soil A; A-2-7/GP/CH											
Test	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
MDD (g/cm^3)	1.76	2.1	1.95	1.98	2.1	2.3	2.5	2.6	2.8	3.2	3.6	3.9	4.3	4.8
OMC (*w*)(%)	13.1	11.2	12.4	12.2	11.3	10.2	9.8	9.6	9.2	8.8	8.4	8.4	8.4	8.4
G_S	2.6	2.8	2.7	2.9	3.1	3.2	3.4	3.5	3.7	3.8	3.8	3.9	3.9	4.2

Table 8. Effect of CWCbGPC on the compaction of treated soil B.

			Compaction of CWCbGPC % by weight treated soil B; A-2-6/GP											
Test	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
MDD (g/cm^3)	1.85	2.7	2.8	2.8	2.8	2.9	3.4	3.8	4.2	4.4	4.7	4.9	4.9	5.1
OMC (*w*)(%)	16.2	14.2	13.4	13.3	13.3	13.1	12.4	12.4	10.5	9.4	9.1	8.9	7.8	7.4
G_S	2.43	2.5	2.7	2.9	3.2	3.4	3.6	3.7	3.8	3.9	4.3	4.5	4.7	4.8

Table 9. Effect of CWCbGPC on the compaction of treated soil C.

			Compaction of CWCbGPC % by weight treated soil C; A-7/GP/CH											
Test	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
MDD (g/cm^3)	1.80	1.85	1.85	1.87	1.88	1.94	1.98	2.13	2.4	2.7	2.9	3.1	3.6	3.9
OMC (*w*)(%)	13.13	12.5	12.2	12.1	11.6	10.4	9.8	9.6	9.2	8.7	8.5	8.2	8.0	7.6
G_S	2.12	2.4	2.3	2.4	2.5	2.7	2.8	2.9	3.3	3.6	3.8	3.9	4.1	4.3

1.8 to 1.5% which remained constant throughout the curing sequence, a behaviour attributable to the microscopic swelling where water dipoles are absorbed between platelets (Kayabali and Demir 2011; Pimentel 2015; Ghosh, Kumar, and Krishanu 2016; Hamidi, Man, and Azizli 2016; Hariz et al. 2017). But in the case of soils B and C, it recorded a consistent increase with increase in curing time and a consistent decrease with increase in varied proportions of CWCbGPC. The reduced swelling potential along the increased CWCbGPC is due to the higher content of sodium silicates activator that tends to increase the release of Ca^{2+}, Si^{4+} and Al^{3+} from the MS grains, which eventually speeded 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 soils matrixes reducing swelling potential. On the other hand, the decrease in swelling potential might also be due to the CWCbGPC acting as fillers to reduce the porosity of the treated soils thereby reducing swelling potential. However, the increased swelling potential 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; Muthukumar, Sekar, and Shukla 2018).

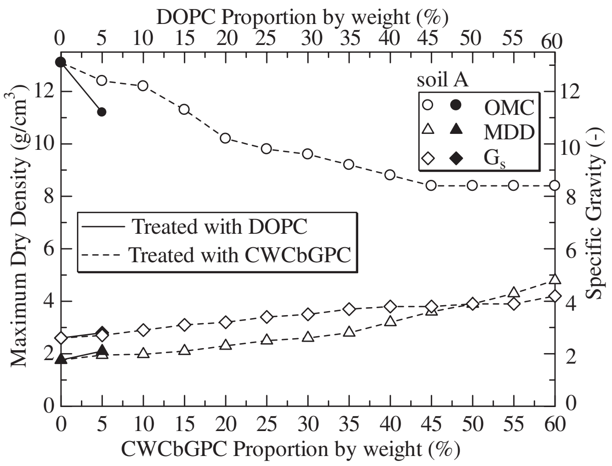

Figure 7. Compaction behaviour of treated soil A.

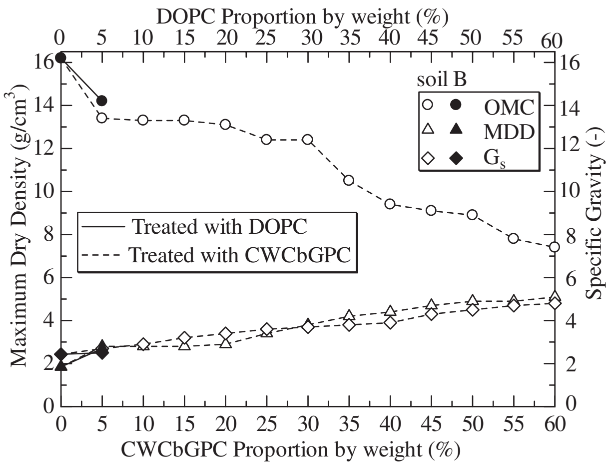

Figure 8. Compaction behaviour of treated soil B.

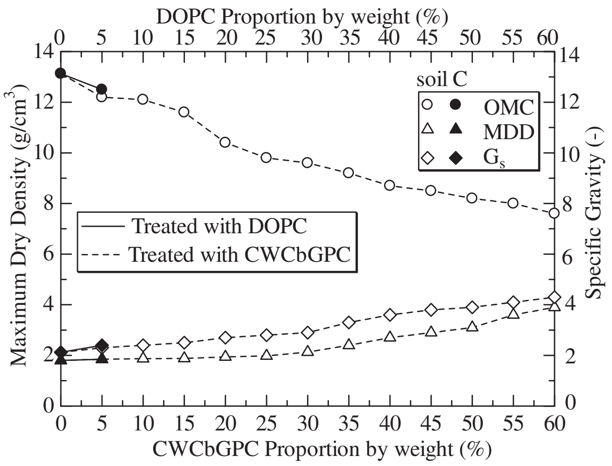

Figure 9. Compaction behaviour of treated soil C.

However, further increase in curing time increases the porosity of cemented matrix with a consequent increase in swelling potential values (Abdel-Gawwad and Abo-El-Enein 2016).

3.5. Drying shrinkage behaviour of DOPC and CWCbGPC treated test soils

The drying shrinkage behaviour of the DOPC and CWCbGPC treated soils were presented in Tables 13–15, Figures 13–15 which represent soils A, B and C, respectively. Both control experiments, and the treated exercises showed a consistent increase in the swelling potential with the curing time. Conversely, the swelling potential decreased with increase in the addition of CWCbGPC. It is important to note at this stage that the lesser the shrinkage limits, the higher the potential for change in volume of soil both treated and untreated (Muthukumar, Sekar, and Shukla 2018). It is observed that the SL of the natural soil recorded 8% for soil A and 7% for soils A and B at 4 h of drying time which is considered to be undergoing severe volume change. This result improved with the increase in drying time. Unfortunately, with the addition of 5% DOPC, the value dropped to 5, 4 and 5% for soils A, B and C, respectively, which supports the high tendency for cemented soils to exhibit shrinkage. But in CWCbGPC soil blends under varied proportions, the SL consistently improved for the three test soils. This improvement was more pronounced with soil B which recorded a SL of 75% at 60% CWCbGPC after 24 h of drying time while soils A and C with higher clay contents (CH) recorded a SL of 65% under the same conditions, which shows that mineral composition is a factor to be considered because it affects shrinkage potentials of treated soils (Skvara, Jilek, and Kopecky 2005; Thakur and Singh 2005; Pimentel 2015).

3.6. Strength development and durability of DOPC and CWCbGPC treated test soils

The addition of the CWCbGPC to the test soils A, B and C consistently increased the compressive strength of the soils at a curing period of 28 days as presented in Table 16-18, Figures 16-18. Twenty Eight (28) days curing time was used here because strength development and durability of the treated matrix are the primary properties being evaluated. The soils mixed with the additive geopolymer maintained a consistent improvement, which showed that further addition will bring further increase in the strength of the treated soil. The presence of the geopolymer in the soils increased the strength properties of the blended mixture attributed to the physicochemical, aluminosilicate and highly pozzolanic properties of the CWCbGPC and to its ability to reduce adsorbed water thereby making soils with higher clay content to behave like granular soils. These result values satisfy the 'very stiff' and 'hard' materials at 45, 50, 55 and 60% by weight addition of geopolymer material for soils A and B, and 50, 55 and 60% for soil C, a material condition for use as a sub-base material for pavement construction (Arioz et al. 2006; Davidovits 2013; ASTM C618 2014). Additionally, increase in the additives (CWCbGPC) concentration resulted in increasing of compressive strength at increased strain. By addition of CWCbGPC, the uncemented soil samples became denser by filling some voids in the soil samples structure. Also, the good dispersion of the geopolymer particles by addition of CWCbGPC led to a better filling of free spaces between the soil particles, which improved the porosity and more resistant soil samples. Additionally, the

Table 10. Effect of CWCbGPC on the swelling potential of treated soil A.

			Swelling potential (%) of CWCbGPC % by weight treated soil A; A-2-7/GP/CH											
Curing time (days)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
0	4.5	2.5	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.2	1.5	1.5	1.5
3	5.9	4.2	3.5	2.8	2.7	2.7	2.7	2.7	2.7	2.7	2.4	2.2	2.2	1.8
7	7.8	5.8	4.2	3.1	2.9	2.9	2.9	2.9	2.9	2.9	2.7	2.5	2.3	1.5
14	8.3	6.6	5.1	4.4	3.1	3.1	3.1	3.1	3.1	3.1	2.9	2.7	2.5	1.5
28	9.6	7.2	6.7	4.8	4.5	4.5	4.5	4.5	4.5	4.5	3.2	2.9	2.6	1.5
56	10.5	8.9	7.7	5.2	4.9	4.9	4.9	4.9	4.9	4.9	4.5	3.1	2.9	1.5
72	14.2	9.6	8.4	7.5	6.2	6.2	6.2	6.2	6.2	6.2	5.8	3.1	2.3	1.5

Table 11. Effect of CWCbGPC on the swelling potential of treated soil B.

			Swelling potential (%) of CWCbGPC % by weight treated soil B; A-2-6/GP											
Curing time (days)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
0	4.2	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.2	1.0	1.0	1.0
3	5.6	2.2	2.0	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.4	1.2	1.2	1.2
7	6.8	2.8	2.5	2.1	1.9	1.9	1.9	1.9	1.9	1.9	1.7	1.5	1.5	1.5
14	7.3	3.6	3.0	2.4	2.1	2.1	2.1	2.1	2.1	2.1	1.9	1.7	1.7	1.7
28	8.7	4.0	3.4	2.9	2.5	2.5	2.5	2.5	2.5	2.5	2.2	1.9	1.9	1.9
56	9.5	4.8	3.8	3.2	2.9	2.9	2.9	2.9	2.9	2.9	2.5	2.1	2.1	2.1
72	12.8	5.6	4.0	3.6	3.2	3.2	3.2	3.2	3.2	3.2	2.8	2.1	2.1	2.1

Table 12. Effect of CWCbGPC on the swelling potential of treated soil C.

			Swelling potential (%) of CWCbGPC % by weight treated soil C; A-7/GP/CH											
Curing time (days)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
0	5.5	4.5	4.4	3.4	3.2	2.8	2.4	2.2	1.5	1.5	1.5	1.5	1.5	1.5
3	6.0	5.2	4.5	3.8	3.7	3.4	3.1	2.5	2.0	1.5	1.5	1.5	1.5	1.5
7	6.2	5.8	5.2	4.1	3.9	3.8	3.5	2.8	2.4	1.5	1.5	1.5	1.5	1.5
14	8.5	7.6	6.1	5.4	4.1	4.0	3.6	3.2	2.8	1.5	1.5	1.5	1.5	1.5
28	9.8	8.2	7.7	6.8	5.5	5.2	4.2	3.8	3.2	2.5	2.5	2.5	2.5	2.5
56	11.5	8.9	8.7	7.2	6.8	6.2	5.5	4.3	3.8	2.5	2.5	2.5	2.5	2.5
72	14.8	9.6	8.7	7.5	7.0	6.6	6.1	5.2	4.8	2.5	2.5	2.5	2.5	2.5

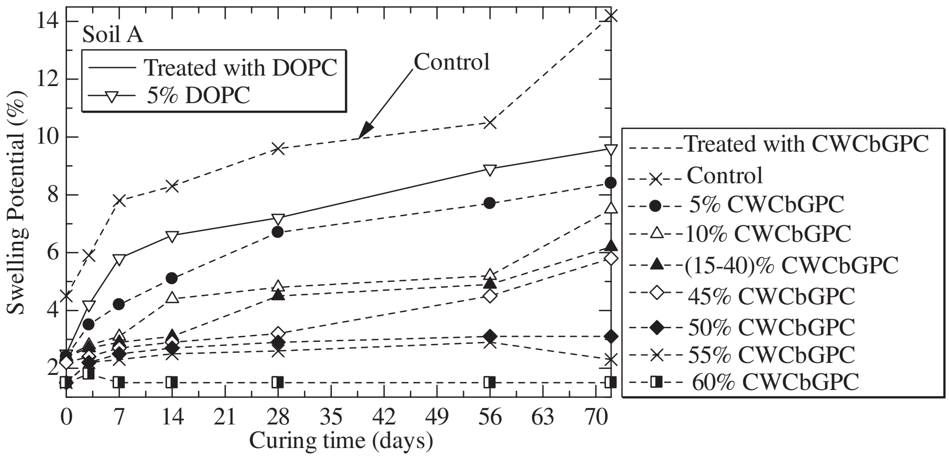

Figure 10. Effect of CWCbGPC on the swelling potential of treated soil A.

increase in CWCbGPC concentration increased the interconnection between soil particles and produced more homogenous compressible material. Therefore, the CWCbGPC had a considerable effect on increasing the unconfined compressive strength of the uncemented test soils.

Tables 19–21, Figures 19–21 has presented the loss of strength on immersion test results and the durability potential of cemented and uncemented test soils treated with CWCbGPC. This was a test conducted on the DOPC and CWCbGPC materials treated soils for use in pavement construction and other Geotechnical engineering works as a moisture (hydraulically) bound material (HBM) (Fwa 2006). The control test showed that the untreated natural soils were not durable with a durability potential of 72.80, 79.4 and 69.3%, respectively less than 80% while the cemented soil gave a durability potential of 66.7, 77.3 and 64.6%, respectively (Osinubi 2000; Osinubi, Bafyau, and

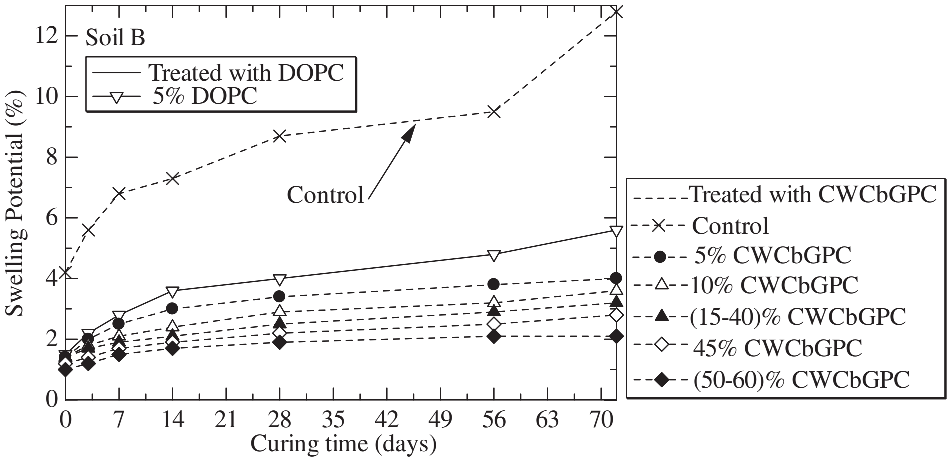

Figure 11. Effect of CWCbGPC on the swelling potential of treated soil B.

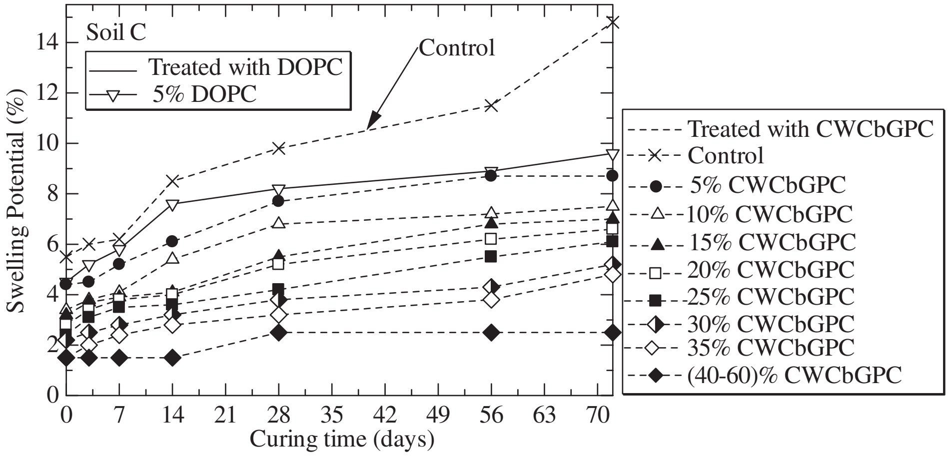

Figure 12. Effect of CWCbGPC on the swelling potential of treated soil C.

Table 13. Effect of CWCbGPC on the drying shrinkage of treated soil A.

			Drying shrinkage (%) of CWCbGPC % by weight treated soil A; A-2-7/GP/CH											
Oven time (hours)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
4	8	5	8	8	8	8	8	8	8	8	8	8	8	8
8	13	8	13	14	15	18	22	24	26	28	31	33	35	36
12	16	11	18	19	21	23	25	28	31	33	35	39	42	45
16	21	14	27	29	32	34	37	38	41	43	45	47	52	55
20	24	18	28	30	32	35	37	40	43	45	48	50	54	60
24	28	21	32	34	36	38	41	45	48	51	53	55	59	65

Table 14. Effect of CWCbGPC on the drying shrinkage of treated soil B.

			Drying shrinkage (%) of CWCbGPC % by weight treated soil B; A-2-6/GP											
Oven time (hours)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
4	7	4	7	7	7	7	8	8	8	8	8	8	8	8
8	10	5	10	12	15	17	28	32	39	42	45	48	50	55
12	12	7	13	15	17	19	36	40	45	48	50	53	55	58
16	15	9	17	19	22	24	38	45	48	55	58	60	62	64
20	18	11	19	21	24	27	41	48	52	58	60	65	67	70
24	20	12	22	25	27	32	45	53	55	60	65	68	70	75

Table 15. Effect of CWCbGPC on the drying shrinkage of treated soil C.

			Drying shrinkage (%) of CWCbGPC % by weight treated soil C; A-7/GP/CH											
Oven time (hours)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
4	7	5	8	8	8	8	8	8	8	8	8	8	8	6
8	11	8	12	13	15	17	20	23	25	27	30	32	35	35
12	16	12	18	19	21	23	25	28	31	33	35	39	42	45
16	20	14	26	28	30	32	35	37	40	42	45	47	51	55
20	23	18	28	30	32	35	37	40	43	45	48	50	54	60
24	27	20	32	34	36	38	41	45	48	50	52	55	59	65

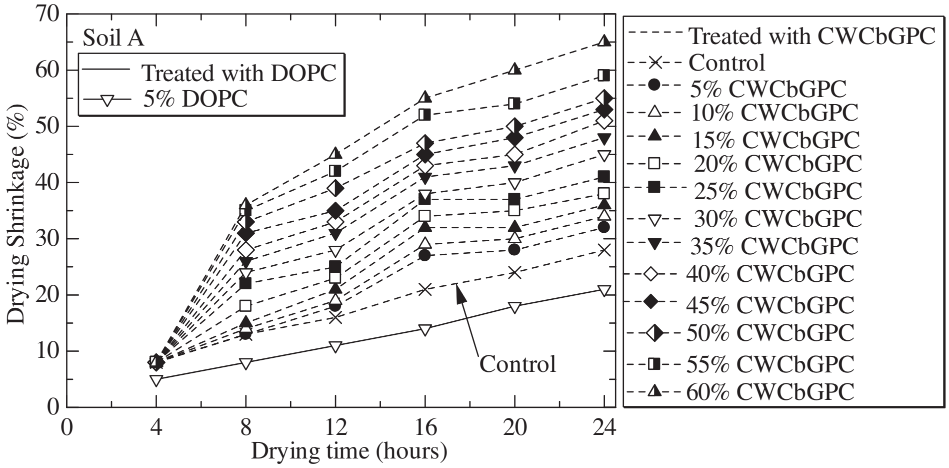

Figure 13. Effect of CWCbGPC on the drying shrinkage of treated soil A.

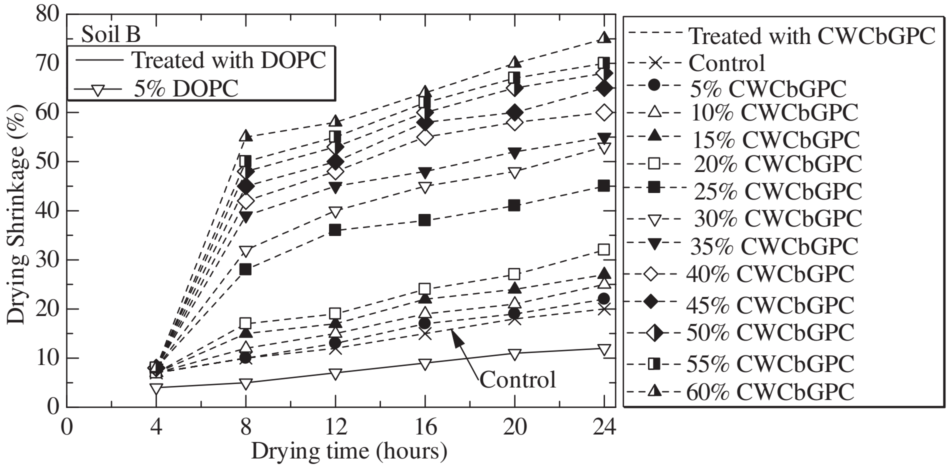

Figure 14. Effect of CWCbGPC on the drying shrinkage of treated soil B.

Eberemu 2009; Onyelowe 2017a, 2017b, 2017c; Onyelowe and Van Bui 2018a, 2018b). The behaviour of the durability of the cemented soil is attributed to the high shrinkage and crack tendency of cement at the early life of cemented materials creating spaces for moisture to be absorbed thereby reducing the durability of cemented geotechnical facilities (Davidovits 2013). But on the addition of different rates of varied rates of CWCbGPC, the durability potential increased considerably and consistently. The matrix suction on immersion may have affected the strength of the CWCbGPC treated soil, but the results remained within the limits of durability (i.e. greater than 80%). This may be due to the fact that the CWCbGPC material showed strong pozzolanic and aluminosilicate properties because of the strong cations released at the adsorbed complex as to form a strong resistance to the effect of moisture on immersion. Also, the reaction between the soil anion and the geopolymer materials cations at the adsorbed complex contributed to the formation of fluccs and eventual densification, polycondensation and durable strength gain, which resisted the effect of absorption at the immersion of the treated test soils.

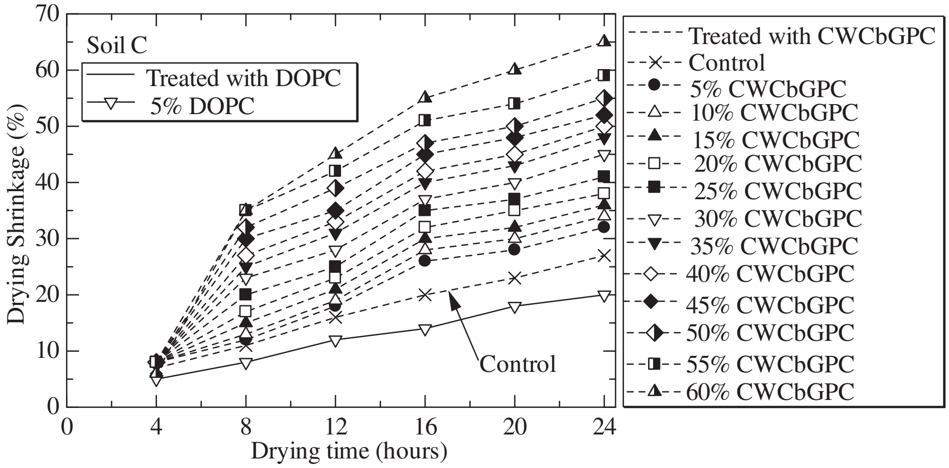

Figure 15. Effect of CWCbGPC on the drying shrinkage of treated soil C.

Table 16. Effect of CWCbGPC on the compressive strength properties of treated test soil A at 28 days.

	Axial stress (kN/m^2)		Axial stress (kN/m^2)of CWCbGPC % by weight treated soil A; A-2-7/GP/CH											
Test strain (%)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.05	95.5	96.4	96.4	108	124	142	148	152	157	160	172	198	198	198
0.1	115.5	118.5	118.8	128	143	165	170	178	182	186	198	221	221	221
0.15	118.6	120.4	121.4	132	165	186	188	196	200	206	223	243	243	243
0.2	135.7	138.4	138.6	140	176	197	200	214	219	224	248	265	265	265
0.25	143.5	149.5	149.6	160	185	210	218	223	228	234	264	285	285	285
0.3	147.7	156.6	157.5	170	194	218	221	229	235	238	284	302	302	302
0.35	149.8	162.8	162.4	185	200	228	230	238	245	249	302	334	334	334
0.4	154.4	174.3	174.9	198	208	234	238	241	248	256	322	356	356	356
0.45	158.5	182.5	183.1	201	219	245	250	258	262	276	338	376	376	376
0.5	159.9	188.5	188.6	206	226	258	262	274	285	288	348	389	389	389
0.55	162.7	190.6	191.8	218	234	261	268	281	295	297	355	406	406	406
0.6	168.0	192.4	192.9	222	248	278	281	289	299	307	371	420	420	420
0.65	171.5	196.5	197.4	228	256	289	292	299	308	312	388	448	448	448
0.7	175.6	198.4	198.8	232	265	301	310	317	318	321	400	462	462	462
0.75	178.9	201.4	202.4	238	276	316	321	326	328	331	424	482	482	482
0.8	180.6	202.5	202.8	243	286	324	328	332	337	340	442	501	501	501
0.85	183.5	203.4	203.8	245	291	342	348	351	362	369	462	519	519	519
0.9	184.6	205.3	205.8	255	298	354	361	369	376	380	480	537	537	537
0.95	185.9	206.5	207.0	261	302	368	371	382	393	396	500	556	556	556
1.00	196.6	208.1	208.0	267	316	380	392	398	400	405	520	570	570	570

Table 17. Effect of CWCbGPC on the compressive strength properties of treated test soil B at 28 days.

	Axial stress (kN/m^2)		Axial stress (kN/m^2)of CWCbGPC % by weight treated soil B; A-2-6/GP											
Test strain (%)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.05	98	100	98	106	126	144	149	153	157	160	172	200	200	200
0.1	119	119	119	124	145	165	171	178	182	186	198	225	225	225
0.15	121	122	122	130	165	186	188	196	202	216	223	243	243	243
0.2	135	138	138	141	175	199	203	214	219	224	248	265	265	265
0.25	141	141	149	162	188	210	218	223	228	234	264	285	285	285
0.3	146	156	157	171	198	218	221	229	235	238	284	312	312	312
0.35	150	162	163	184	201	228	230	238	245	249	302	334	334	334
0.4	158	174	174	197	208	234	238	241	248	256	322	356	356	356
0.45	159	181	183	202	218	245	251	258	262	276	338	376	376	376
0.5	159	188	188	206	226	258	262	274	285	288	348	389	389	389
0.55	163	190	191	219	234	261	268	281	295	297	355	406	416	416
0.6	169	192	192	224	249	278	282	289	299	307	371	425	425	425
0.65	178	196	197	229	256	289	292	299	308	312	388	448	448	448
0.7	178	197	198	233	265	304	312	317	318	321	412	462	462	462
0.75	178	201	202	238	277	316	321	326	328	331	424	482	482	482
0.8	181	202	202	244	286	324	328	332	337	342	442	511	511	511
0.85	183	203	203	248	294	342	348	352	362	369	462	529	529	529
0.9	184	205	205	255	298	354	361	369	376	380	481	537	537	537
0.95	186	206	207	261	317	368	371	382	393	396	510	556	556	556
1.00	192	208	208	268	325	381	393	398	400	415	522	578	578	578

Table 18. Effect of CWCbGPC on the compressive strength properties of treated test soil C at 28 days.

	Axial stress (kN/m²)		Axial stress (kN/m²)of CWCbGPC % by weight treated soil C; A-7/GP/CH											
Test strain (%)	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.05	90	102	91	94	96	97	99	99	120	134	154	165	173	185
0.1	97	116	99	103	104	105	107	107	132	148	165	188	198	205
0.15	100	118	102	105	106	107	109	109	145	159	178	208	216	228
0.2	103	120	105	107	108	109	111	111	154	168	198	224	242	255
0.25	105	123	108	110	113	115	117	117	161	176	213	243	265	284
0.3	109	126	111	113	114	117	118	118	174	186	226	258	278	301
0.35	113	129	114	118	119	121	123	123	185	198	238	268	296	328
0.4	117	130	119	120	122	123	125	125	195	210	248	277	312	345
0.45	121	132	123	124	125	126	129	129	208	220	254	298	328	365
0.5	123	134	126	129	130	132	133	133	219	235	269	312	337	378
0.55	127	138	129	132	133	135	137	137	225	246	284	326	349	394
0.6	130	145	130	135	136	137	139	139	234	265	296	338	354	409
0.65	134	148	135	138	139	139	142	142	245	278	307	348	361	423
0.7	139	150	140	143	144	145	147	147	258	288	316	356	377	437
0.75	142	153	144	146	148	149	152	152	267	296	325	364	381	454
0.8	148	155	149	152	156	158	159	159	272	316	338	372	398	469
0.85	150	169	152	154	157	159	163	163	286	328	345	381	417	472
0.9	154	170	156	164	168	169	171	171	294	342	358	400	428	484
0.95	164	185	166	176	178	179	182	182	298	354	366	420	434	491
1.00	176	190	178	180	182	184	189	189	306	366	375	442	440	505

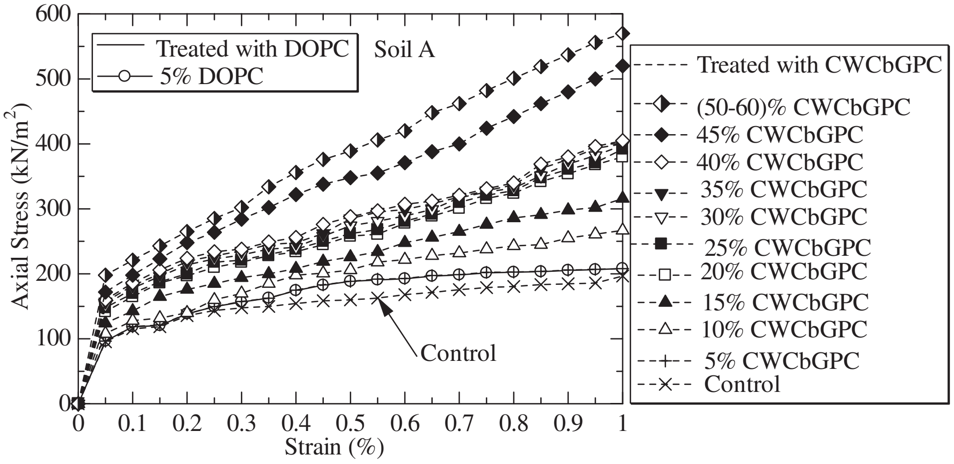

Figure 16. Effect of CWCbGPC on the compressive strength properties of treated test soil A.

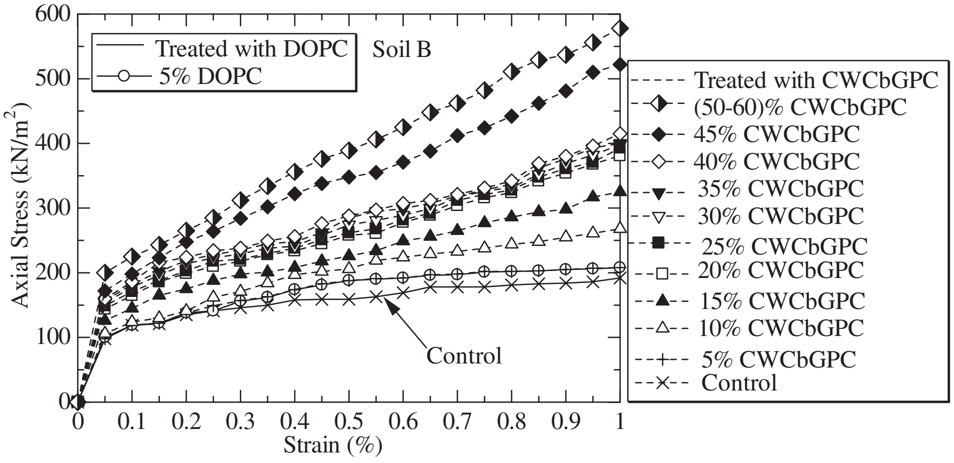

Figure 17. Effect of CWCbGPC on the compressive strength properties of treated test soil B.

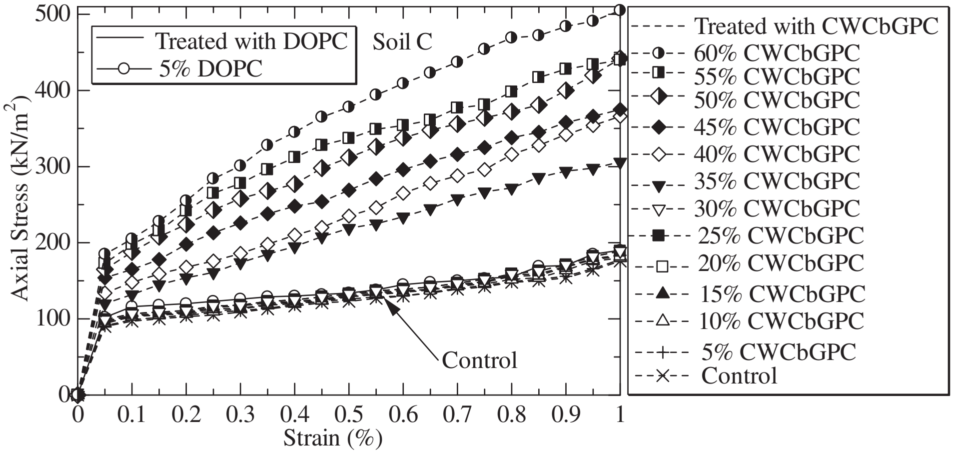

Figure 18. Effect of CWCbGPC on the compressive strength properties of treated test soil C.

Table 19. UCS loss of strength on immersion and the durability index of CWCbGPC treated soil A.

			UCS and durability index of CWCbGPC % by weight treated soil A; A-2-7/GP/CH											
Test	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
28 days open air curing (kN/m^2)	220.5	225	225	248	256	272	286	298	312	325	338	347	356	364
14 days open air curing + 14 days immersed curing (kN/m^2)	160.5	150	185	220	232	256	269	281	298	312	325	330	338	342
Durability index (%)	72.8	66.7	82.2	88.7	90.6	94.1	94.1	94.3	95.5	96.0	96.2	95.1	94.9	94.0

Table 20. UCS loss of strength on immersion and the durability index of CWCbGPC treated soil B.

			UCS and durability index of CWCbGPC % by weight treated soil B; A-2-6/GP											
Test	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
28 days open air curing (kN/m^2)	215.4	220	225	234	242	258	269	278	290	312	324	344	356	388
14 days open air curing + 14 days immersed curing (kN/m^2)	171	170	185	194	203	219	229	238	256	303	316	329	338	356
Durability index (%)	79.4	77.3	82.2	82.9	83.8	84.9	85.1	85.6	88.3	97.4	97.5	956	94.9	91.8

Table 21. UCS loss of strength on immersion and the durability index of CWCbGPC treated soil C.

			UCS and durability index of CWCbGPC % by weight treated soil C; A-7/GP/CH											
Test	Control	5% DOPC	5	10	15	20	25	30	35	40	45	50	55	60
28 days open air curing (kN/m^2)	180.5	198	201	228	245	252	267	285	302	324	324	324	300	300
14 days open air curing + 14 days immersed curing (kN/m^2)	125	128	180	205	220	226	238	255	271	289	285	281	256	245
Durability index (%)	69.3	64.6	89.6	89.9	89.8	89.7	89.1	89.5	89.7	89.2	88.0	86.7	85.3	81.7

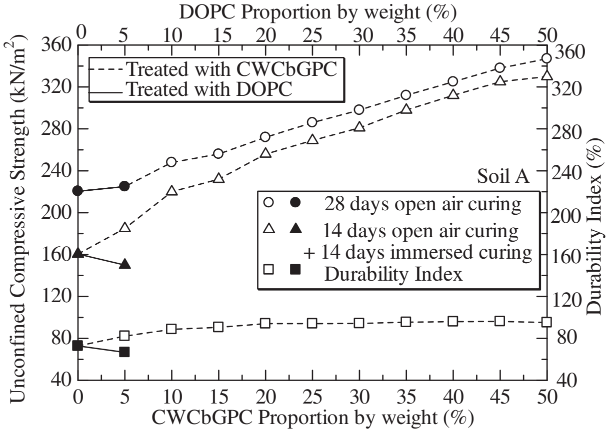

Figure 19. Effect of CWCbGPC on UCS loss of strength on immersion and the durability index – soil A.

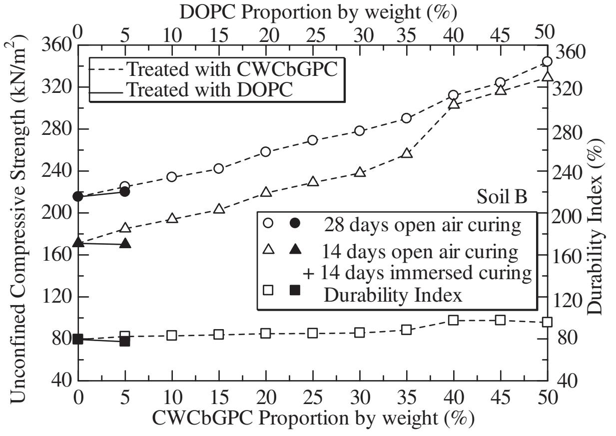

Figure 20. Effect of CWCbGPC on UCS loss of strength on immersion and the durability index – soil B.

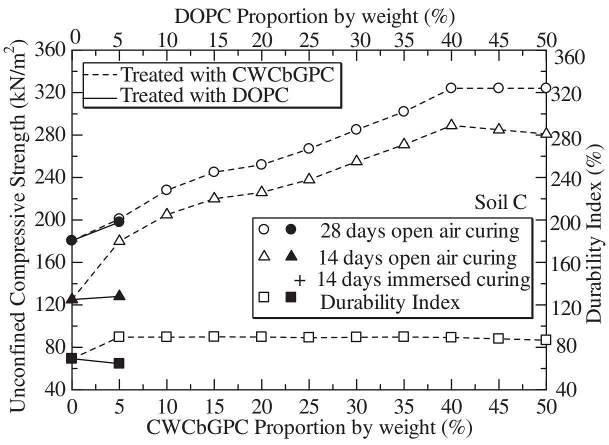

Figure 21. Effect of CWCbGPC on UCS loss of strength on immersion and the durability index – soil C.

4. Concluding remarks

The swelling, shrinkage and strength development behaviour of cemented and uncemented soils A, B and C treated with CWCbGPC have been studied under the laboratory conditions and the following concluding remarks can be made;

(i) The consistency and compaction tests evaluations showed significant with varied proportions of CWCbGPC soil blends.
(ii) The swelling potential of the treated soils improved consistently with increased proportions of the CWCbGPC.
(iii) Similarly, the shrinkage limits improved consistently with increased and varied proportions of the GPC unlike the soil DOPC blend which deteriorated with addition of 5% DOPC for the test soils and gave credence to the high shrinkage tendency of cemented matrixes.
(iv) The strength development and durability of the treated soil improved consistently also. But the durability of the cemented soils was impaired and showed that cemented soils under hadraulically bound medium or conditions or long moisture exposures are not durable as a result of the high shrinkage potential of Portland cements.

Generally, the above exercise has shown that CWCbGPC can totally replace DOPC in the treatment of soils for hydraulically bound purposes; highway pavement foundations, airfield pavement foundations, substructures and other hydraulic structures for more durable structures resistant to heat or temperatures above 600C, acid attacks, sulphate attacks, fire, etc. and functioned well as fillers, which improved the porosity of the treated soils enhancing the densification, flocculation, polycondensation, strength development and durability of the treated soils. Finally, having shown consistent progress in the durability index, it also shows that beyond the highest proportion and beyond the 28 days, CWCbGPC will stand these effects over time.

Disclosure statement

No potential conflict of interest was reported by the authors.

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