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Triaxial and density behaviour of quarry dust based geopolymer cement treated expansive soil with crushed waste glasses for pavement foundation purposes

Kennedy Onyelowe[a,b]*, Clifford Igboayaka[c], Francis Orji[d], Henry Ugwuanyi[a], Duc Bui Van[b]

[a]*Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, P. M. B. 7267, Umuahia 440109, Abia State, Nigeria*
[b]*Research Group of Geotechnical Engineering, Construction Materials and Sustainability, Hanoi University of Mining and Geology, Hanoi, Vietnam*
[c]*Department of Mechanical Engineering, Michael Okpara University of Agriculture, Umudike, P. M. B. 7267, Umuahia 440109, Abia State, Nigeria*
[d]*Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike, P. M. B. 7267, Umuahia 440109, Abia State, Nigeria*

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Abstract

The effect of quarry dust based geopolymer cement (QDbGPC) and crushed waste glasses (CWG) on the triaxial and density characteristics of expansive test soil was investigated under laboratory conditions. Quarry dust is a solid waste the management of which poses a big problem to construction and environmental experts. So also is the management of waste glasses. Then again, the use conventional cement poses everyday threat to the environment as its utilization releases huge amount of CO_2 to the environment thereby causing increased global warming. However, the utilization of quarry dust in the synthesis of geopolymer cements which is an eco-friendly geomaterial and by extension its use in the soil treatment protocol is the aim of this work. The test soil was observed to be a poorly graded A-2-6 soil according to USCS and AASHTO classification systems respectively. The treatment exercise showed that the shear characteristics of the treated soil improved consistently. The poisson ratio, porosity and submerged density improved with increased additives. The stress-strain relationship improved to a very stiff consistency which satisfies the requirements for subgrade and subbase materials in pavement construction. Finally, the utilization of QDbGPC proved to be a good replacement for conventional cement in terms of environmental issues resulting from CO_2 emission, resistant to moisture, heat, sulphate attacks, etc on hydraulically bound materials.

Keywords: Triaxial behaviour; Dry density behaviour; Quarry dust based geopolymer cement; Moisture bound materials; Recycled waste materials

1. Introduction

Pavement foundation constitutes the borrowed or in situ compacted subgrade layer, subbase materials and base course materials [1-3]. The top most two layers are placed over the subgrade layer to act as the fundamental foundation base to receive traffic and dynamic load from the entire pavement. In most cases, borrowed or in situ compacted subgrade soils fail the basic requirements for use as foundation materials [4-10]. This is as a result of the soils possessing characteristics like high swelling potentials, low shrinkage limits, high plasticity, poor grading, low California bearing ratio below 10% as the case may be, and high expansivity [10-13]. Soils with the listed characteristic features are unfit for use as foundation materials. This situation may be remedied by improving the structural, physical, physicochemical, mechanical and geotechnical properties of the soils before due consideration for use as a foundation material [10,14-18]. This is achieved through the utilization of additives or admixtures with cementing properties. These additives are considered geomaterials of high aluminosilicates compounds content, which are compounds responsible for densification and strengthening of treated soils under the influence of moisture [19-24]. Expansive soils, which are called vertisols are clayey soils which when experiences changes in moisture content are prone to large changes in volume viz swelling and shrinking and an attendant cracking properties subject to season changes over time [25]. These cracks are fissures that facilitate the ingress or penetration of water causing swelling and shrinkage cycles, which cause steady stress on pavement structures and eventual damage [26-31]. These continuous changes in soil volume cause homes built on soils to

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*Corresponding author.
E-mail addresses: konyelowe@mouau.edu.ng; konyelowe@gmail.com (Kennedy Onyelowe); ekene.igboayaka@mouau.edu.ng (Clifford Igboayaka), nkemdirim.orji@mouau.edu.ng (Francis Orji), henrykene9@gmail.com (Henry Ugwuanyi), buivanduc@humg.edu.vn (Duc Bui Van).

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unevenly move and consequently experience cracks [32]. Vertisols also cause basement and foundation problems [33]. Hence, expansive soils or vertisols are unsuitable materials for construction purposes more especially in hydraulically bound zones [34-36]. However, through some proportionate treatment protocol, these vertisols could be managed to become good geomaterials used in various ways as foundation materials, backfills, landfills, slopefills, etc. In the past decades, solid waste materials have been applied as soil improvement materials. These materials are added as a percentage by weight of the dry matrix and the behaviour of the treated soil studied to observe the effect of the additives [37-42]. Moving forward, the solid wastes have been converted to ash by direct combustion to produce amorphous materials with high pozzolanic properties. Studies have shown great improvement in the properties of expensive soils when treated with ash materials like palm bunch ash, palm kernel shell ash, bagasse ash, rice husk ash, groundnut shell ash, egg shell ash, etc or other solid recycled waste materials like quarry dust, crushed waste glasses, crushed waste ceramics, crushed oyster shells, crushed snail shells, crushed periwinkle shells, crushed egg shells, etc. In most cases, ordinary Portland cement is added to support the cementing or binding properties of the ash materials [43-49]. The utilization of cement has been a source of CO_2 emission, which contributes to global warming and attempts are being made to reduce to zero the use of ordinary cement as a construction material. To fully introduce the era of eco-friendly construction, geomaterials or green materials or geopolymer cements are being synthesized for various needs in the construction industry [50-51]. Research results have shown that these geomaterials or geopolymer cements have shown great advantage over ordinary cement hence a successful replacement. They exhibit resistant characteristics to heat, shrinkage, cracking, swelling, and all forms of volume changes, and equally have high cementing and pozzolanic properties. The utilization of crushed waste glasses and quarry dust based geopolymer cement synthesized from quarry dust and metallurgical slag with activators of alkali silicates in the improvement of expansive soil properties is the aim of this work with particular concentration on effect of the additives on the triaxial characteristics, effect of the additives on the dry density potential of the treated soil and effect of the additives on the stress-strain behaviour of the treated soil.

2. Methodology of Research

Crushed waste glasses, quarry dust, metallurgical slag, alkali silicates and test expansive soil are the test materials utilized in this research. General preliminary tests were used to characterize the test soil and test materials in accordance with British standard requirements [52-55]. Then the soil improvement protocol was carried out in accordance with British standard requirements [56].

2.1. Materials Preparation and Sampling

The test soil was collected from a depth of 0.6 meters at Amaba borrow site on coordinates of 5°27'0" North and 7°31'60" East. Crushed waste glasses were collected as broken and waste bottles from Glassforce Industries ltd, Aba dumpsite. These were sundried and crushed in a crushing machine to fineness and stored in silos for use. Quarry dust was collected from the Crush Rock Industries quarry site at Lokpanta, Isiochi, Abia State, Nigeria. This was also sundried for one week and stored in silos for use in the treatment exercise. The quarry dust, and metallurgical slag were used under the influence of alkali activators to synthesize the quarry dust based geopolymer cement adapting the findings of Abdel-Gawwad & Abo-El-Enein [51] and Davidovits [38]. The constituent elements were blended in the proportions; 4.8% activator, plus 55% quarry dust, plus 25% metallurgical slag by weight of solid. This geopolymer cement (GPC) was utilized in proportions by weight of solid to treat the expansive soil.

2.2. Experimental Methods

Adaptable blending procedures were used to carry out the improvement exercise in conformity with the British standard requirements [56]. The compaction test was carried out with the standard proctor method. The GPC was mixed with the treated test soil in the proportions of 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40% with the addition of crushed waste glasses in the proportions of 10%, 20%, 30% and 40% by weight of solid. A total of 45 specimens were prepared and tested for compaction behaviour. Triaxial test was conducted on the treated soil mixed with the above proportions of GPC and CWG in accordance with the British standard requirements [56]. The lateral and axial displacements of the test specimens were observed and recorded. The results were used to estimate the poisson ratio. All other shear characteristic properties were also estimated from the triaxial exercise, which included cohesion, elastic modulus and frictional angle. The unconfined compression test was conducted on the treated soil also in accordance with the British standard [56] to determine the stress-strain behaviour of the test expansive soil. Saturated density, submerged density and void ratio of the treated soil were also determined from the laboratory protocol. Eqs. (1) to (4) were used during the experimental procedure to estimate the physical parameters.

$$\mu = \frac{Lateral\,Displacement}{Axial\,Displacement} \tag{1}$$

$$E = \frac{Stress}{Strain} \tag{2}$$

$$\rho_{sat} = \rho_W \frac{G_S + e}{1 + e} \tag{3}$$

$$\rho^I_{sub} = \rho_W \frac{G_S - 1}{1 + e} \tag{4}$$

where, μ= poisson ratio ; E= modulus of elasticity; ρ_{sat}= saturated density; G_s= specific gravity; e= void ratio; ρ^I_{su}= submerged density.

3. Results and Discussions

3.1. General Behaviour and Classification of Test Materials

In Tables 1,2 and Fig. 1, the results of the preliminary properties of the test soil have been presented. The test soil was classified as A-2-6 soil group according to the AASHTO classification method [1] and GP soil according to unified soil classification system. The test soil has particle size of 10% passing No. 200 sieve. It is a highly plastic and expansive soil with plasticity index of 25%, shrinkage limit of 8% and free swelling index of 234% [56]. Table 3 presents that the test materials have high aluminosilicate content

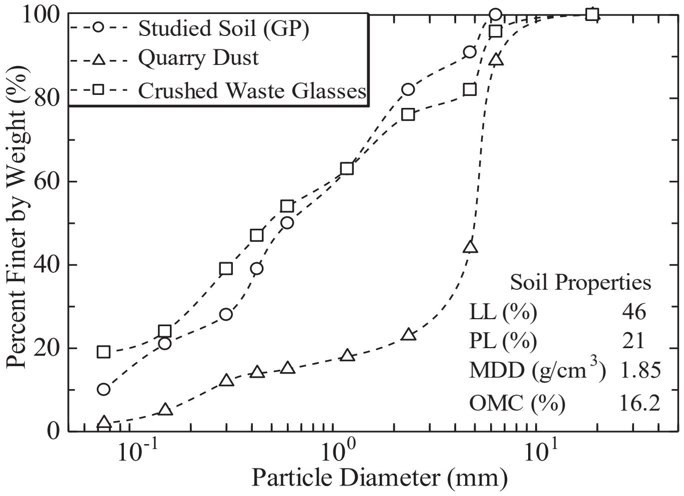

Fig. 1. Particle size distribution of studied materials.

Table 1
Basic properties of the Amaba test soils.

Property Description of test Soils and Units	Values
% Passing Sieve No 200	10
NMC (%)	13.49
LL (%)	46
PL (%)	21
PI (%)	25
SL (%)	8
FSI (%)	234
G_s	2.43
AASHTO Classification	A-2-6
USCS	GP
MDD (g/cm^3)	1.85
OMC (%)	16.2
CBR (%)	13
Color	Reddish Gray

and possess pozzolanic properties [45]. 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 [44]. 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 analyzed 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 [44]. 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 [45].

3.2. Compaction density behaviour of QDbGPC treated soil with CWG

The compaction and density response of the QDbGPC treated soil blended with CWG is presented in Table 4 and Fig. 2. The QDbGPC was added in the proportions of 5% t0 40% in an increment of 5% per specimen while CWG was added into the treated blend in the proportion of 10% to 40% using an increment of 10% per specimen. A total of 45 specimens were prepared and tested. The OMC decreased with steady increase in both QDbGPC and CWG. This maintained a reduction index of about 13% with the addition of QDbGPC and 10% with addition of CWG. This behaviour is attributed to the higher binding potential of QDbGPC over CWG with an associated higher heat of hydration rate. The MDD increased constantly with increased rate of QDbGPC and CWG. The rate of improvement in dry density was recorded as 12% with increased QDbGPC. The rate of improvement in dry density was recorded as 4% with increased CWG. This behaviour is due to the ability of the QDbGPC to react with the treated soil under the influence of water and the aluminosilicates responsible for strength development. The rate of calcination, hydration, pozzolanic and geopolymerization reactions was higher with the GPC than with the CWG. While void ratio of the treated soil reduced with increase in the additive proportions, specific gravity,saturated density and submerged density increased. This behaviour was due to the resistant characteristics of geopolymer cements to moisture effects. However, the blending of the treated soil with the additives replaced the void spaces thereby improving

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

Materials	% Passing sieve (mm)										
	19	6.35	4.75	2.36	1.18	0.6	0.425	0.3	0.15	0.075	Pan
Test Soil	-	100	91	82	63	50	39	28	21	10	0
Quarry Dust	100	89	44	23	18	15	14	12	5	2	0
CWG	100	96	82	76	63	54	47	39	24	19	0

Table 3
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	76.56	15.09	2.30	2.66	0.89	2.10	0.33	0.07	-	-	-	-	-
Quarry Dust	63.48	17.72	5.56	1.77	4.65	2.76	0.01	3.17	0.88	-	-	-	-
CWG	73.5	0.78	8.11	-	1.79	2.09	11.0	-	1.89	-	-	-	0.8
QDbGPC	72.45	4.45	5.85	1.78	2.42	4.83	4.90	0.22	-	-	2.46	-	0.64

*IR is Insoluble Residue, LOI is Loss on Ignition, QD: Quarry Dust, QDbGPC: Quarry Dust base Geopolymer Cement, CWG: Crushed Waste Glasses

Table 4
Compaction density behaviour of QDbGPC treated expansive soil with CWG.

CWG proportion (%)	Material compaction property	Proportion of QDbGPC by weight additive (%)								
		0	5	10	15	20	25	30	35	40
0	OMC(%)	16.2	14.4	12.6	11.5	10.5	9.4	8.5	7.5	7.2
	MDD(g/cm^3)	1.85	1.98	2.05	2.45	2.86	3.12	3.55	3.94	4.18
	G_s	2.43	2.54	2.65	2.73	2.84	2.97	3.04	3.16	3.22
	e	3.1	2.9	2.7	2.5	2.2	1.9	1.6	1.3	1.2
	ρ_{sat}(g/cm^3)	1.35	1.39	1.45	1.49	1.58	1.68	1.78	1.94	2.01
	ρ^{I}_{Sub}(g/cm^3)	0.35	0.39	0.45	0.49	0.58	0.68	0.78	0.94	1.01
10	OMC(%)	15.4	13.6	11.8	10.5	9.3	8.5	7.5	6.4	6.0
	MDD(g/cm^3)	1.96	2.04	2.16	2.56	2.98	3.22	3.65	4.08	4.26
	G_s	2.48	2.68	2.79	2.85	2.95	3.06	3.18	3.28	3.36
	e	2.8	2.7	2.6	2.4	2.1	1.8	1.5	1.2	1.1
	ρ_{sat}(g/cm^3)	1.39	1.45	1.50	1.54	1.63	1.74	1.87	2.04	2.12
	ρ^{I}_{Sub}(g/cm^3)	0.39	0.45	0.50	0.54	0.63	0.74	0.87	1.04	1.12
20	OMC(%)	14.8	12.4	10.8	9.5	8.5	7.4	6.8	5.4	5.0
	MDD(g/cm^3)	2.04	2.15	2.28	2.67	3.05	3.36	3.78	4.18	4.36
	G_s	2.56	2.72	2.86	2.94	3.06	3.18	3.27	3.38	3.42
	e	2.6	2.5	2.4	2.3	1.9	1.7	1.4	1.1	1.0
	ρ_{sat}(g/cm^3)	1.43	1.49	1.55	1.59	1.71	1.81	1.95	2.13	2.21
	ρ^{I}_{Sub}(g/cm^3)	0.43	0.49	0.55	0.59	0.71	0.81	0.95	1.13	1.21
30	OMC(%)	13.2	11.5	9.7	8.8	7.4	6.4	5.5	4.3	4.0
	MDD(g/cm^3)	2.09	2.25	2.34	2.76	3.12	3.45	3.89	4.23	4.45
	G_s	2.65	2.87	2.98	3.03	3.16	3.28	3.34	3.43	3.54
	e	2.5	2.4	2.28	2.2	1.8	1.6	1.3	1.0	0.9
	ρ_{sat}(g/cm^3)	1.47	1.55	1.60	1.63	1.77	1.88	2.02	2.22	2.34
	ρ^{I}_{Sub}(g/cm^3)	0.47	0.55	0.60	0.63	0.77	0.88	1.02	1.22	1.34
40	OMC(%)	12.6	10.4	8.6	7.5	6.4	5.8	4.8	4.1	4.0
	MDD(g/cm^3)	2.15	2.35	2.42	2.86	3.22	3.55	3.95	4.33	4.54
	G_s	2.76	2.96	3.03	3.12	3.28	3.37	3.43	3.56	3.64
	e	2.5	2.3	2.2	2.1	1.7	1.5	1.25	0.98	0.86
	ρ_{sat}(g/cm^3)	1.50	1.59	1.63	1.68	1.84	1.95	2.08	2.29	2.42
	ρ^{I}_{Sub}(g/cm^3)	0.50	0.59	0.63	0.68	0.84	0.95	1.08	1.29	1.42

the porosity of treated matrix and caused a consistent reduction in void ratio. The cation exchange reaction with the adsorbed complex also caused the formation of floccs, which improved the saturated and submerged densities of the treated soil.

3.3. Triaxial behaviour of QDbGPC treated soil with CWG

The shear characteristics of the treated soil were evaluated with the triaxial test results presented in Table 5 and Fig. 3. At the addition of QDbGPC with 0% CWG, the treated soil behaviour with respect to the shear parameters was consistent and improved on the frictional angle, cohesion, and poisson ratio. So also was the elastic modulus behaviour with the addition of QDbGPC. While cohesion recorded an improvement index of 9% with increased QDbGPC at 0% CWG, frictional angle recorded an improvement index of 28%. But on the addition of CWG to the GPC treated soil, there was a drop in the improvement index to about 6%. This behaviour was attributed to the hydration reaction and cation exchange reaction being stalled by the addition of the lower-aluminosilicate-content-CWG. The modulus of elasticity also increased with increase in the rate of QDbGPC by weight. The formation of floccs and strength development in the addition of QDbGPC resulting from the release of Ca++, and silicates within diffused layer interface of the treated soil. The elastic modulus improvement rate increased from 9% at 0% CWG to 11% at 10% CWG by weight. This improved consistent to a recorded 12% improvement index at 40% CWG by weight of solid. This behaviour is due to the addition of the high density crushed waste glasses which improved the densification process and enhanced the rigidity potential of the treated soil. The stress-strain behaviour of the treated soil results were presented in Tables 6 to 10 and Figs. 4 to 8. The stress improved consistently with increased QDbGPC and also with increased CWG. The improvement patterns at increased CWG presented in Figs. 4 to 8 show a consistent pattern. It shows that the vertisol behaved in a similar pattern with the increased CWG. This is due to the physicochemical reactions and pozzolanic characteristics

3.4. Stress-Strain behaviour of QDbGPC treated soil with CWG

The stress-strain behaviour of the treated soil results were presented in Table 6, 7, 8, 9, 10 and Figs. 4, 5, 6, 7 and 8. The stress improved consistently with increased QDbGPC and also with increased CWG. The improvement patterns at increased

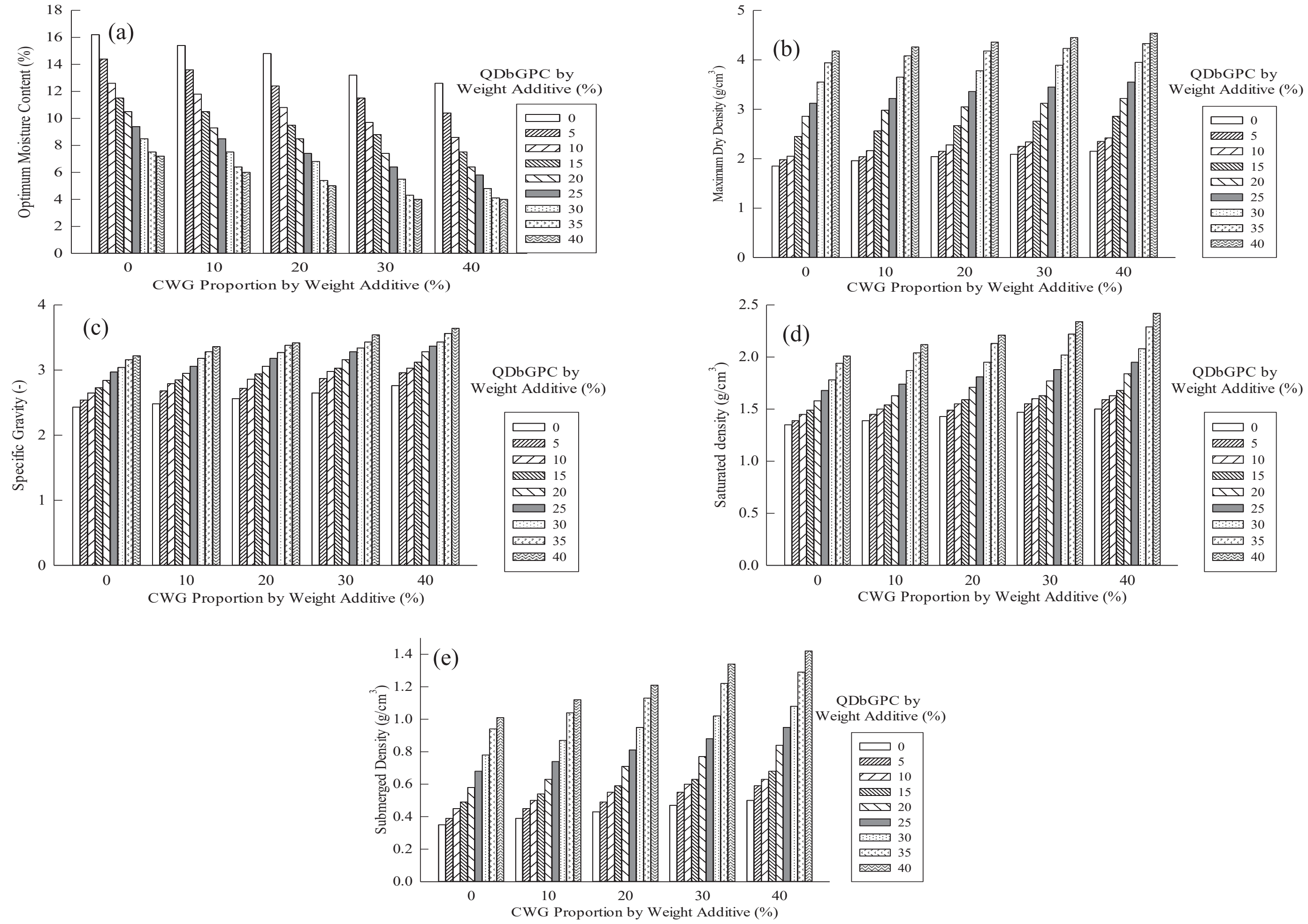

Fig. 2. Compaction density behaviour of QDbGPC treated expansive soil with CWG.

Table 5
Triaxial behaviour of QDbGPC treated expansive soil with CWG.

CWG proportion (%)	Material triaxial property	Proportion of QDbGPC by weight additive (%)								
		0	5	10	15	20	25	30	35	40
0	μ	0.46	0.45	0.44	0.43	0.42	0.41	0.40	0.39	0.38
	C_u	145	154	162	176	185	194	206	218	226
	Ø	12	15	18	23	27	31	35	38	42
	E	124	138	146	158	165	186	208	226	245
10	μ	0.45	0.44	0.43	0.42	0.41	0.40	0.39	0.38	0.37
	C_u	175	185	197	205	218	228	234	241	255
	Ø	20	23	25	27	29	33	37	40	44
	E	128	140	148	160	169	188	210	228	247
20	μ	0.44	0.43	0.42	0.41	0.40	0.39	0.38	0.37	0.36
	C_u	214	225	236	247	258	265	276	284	296
	Ø	28	30	33	35	37	39	41	43	45
	E	130	143	151	162	172	190	215	232	250
30	μ	0.43	0.42	0.41	0.40	0.39	0.38	0.37	0.36	0.35
	C_u	245	256	266	274	285	295	302	318	324
	Ø	35	36	38	40	42	44	45	46	47
	E	133	145	155	164	176	193	218	235	252
40	μ	0.42	0.41	0.40	0.39	0.38	0.37	0.36	0.35	0.34
	C_u	268	277	281	294	306	319	323	338	342
	Ø	46	47	48	49	51	53	55	57	60
	E	135	148	158	169	180	196	220	238	255

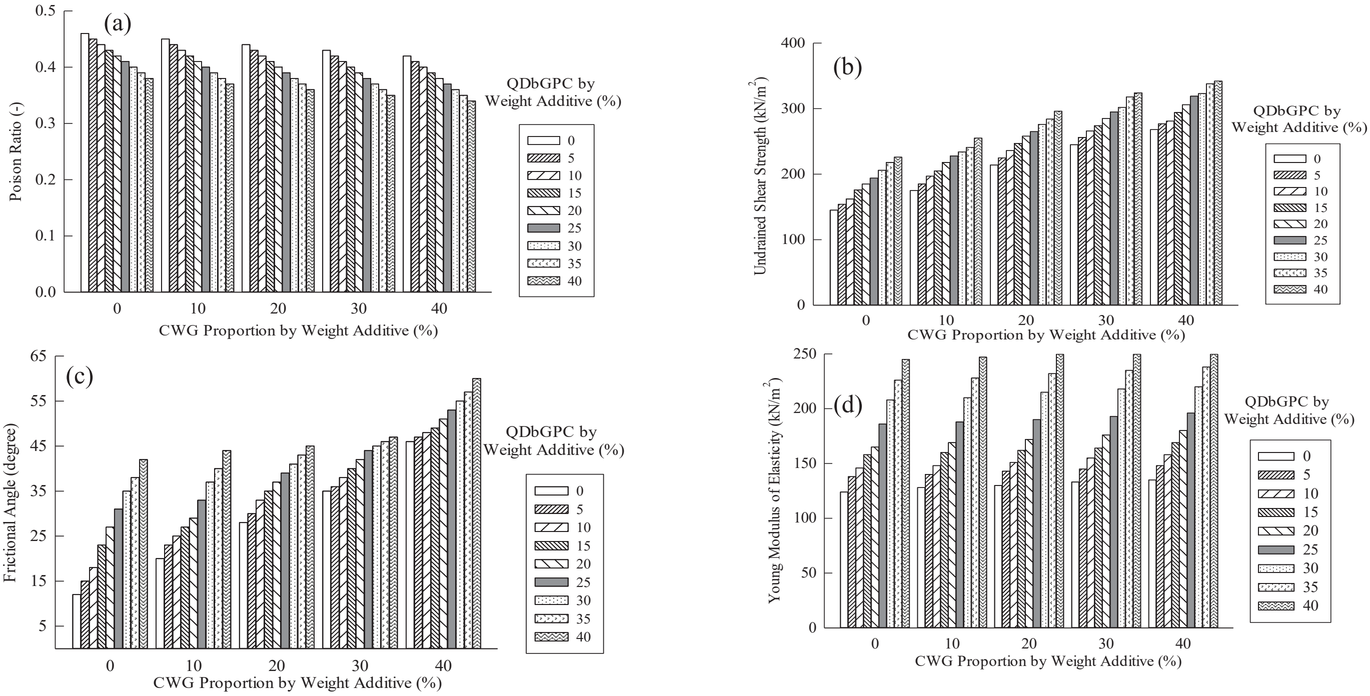

Fig. 3. Triaxial behaviour of QDbGPC treated soil.

Table 6
Axial stress-strain behaviour of 0% CWG (%) and QDbGPC treated cemented soil.

Axial strain (%)	Axial stress (kN/m^2)								
	QDbGPC % by weight treated cemented soil with 0% CWG								
	0	5	10	15	20	25	30	35	40
0.0	0	0	0	0	0	0	0	0	0
0.02	105	110	120	130	160	190	220	255	280
0.04	115	125	130	180	205	210	230	265	305
0.06	120	135	145	195	220	245	260	310	335
0.08	125	145	155	200	225	250	270	320	340
0.10	135	155	180	215	235	265	285	335	355

Table 7
Axial stress-strain behaviour of 10% CWG (%) and QDbGPC treated cemented soil.

Axial strain (%)	Axial stress (kN/m^2)								
	QDbGPC % by weight treated cemented soil with 10% CWG								
	0	5	10	15	20	25	30	35	40
0.0	0	0	0	0	0	0	0	0	0
0.02	107	115	124	135	162	194	224	256	284
0.04	116	128	136	183	210	218	232	266	307
0.06	123	139	147	197	222	248	261	312	336
0.08	128	149	156	205	229	255	274	323	342
0.10	137	160	182	218	236	268	287	337	358

Table 8
Axial stress-strain behaviour of 20% CWG (%) and QDbGPC treated cemented soil.

Axial strain (%)	Axial stress (kN/m^2)								
	QDbGPC % by weight treated cemented soil with 20% CWG								
	0	5	10	15	20	25	30	35	40
0.0	0	0	0	0	0	0	0	0	0
0.02	110	119	128	138	165	198	226	258	286
0.04	121	130	139	185	212	220	234	269	309
0.06	129	142	149	198	225	251	264	315	338
0.08	131	152	158	208	232	259	276	325	345
0.10	140	161	188	219	238	270	289	339	360

Table 9
Axial stress-strain behaviour of 30% CWG (%) and QDbGPC treated cemented soil.

Axial strain (%)	Axial stress (kN/m^2)								
	QDbGPC % by weight treated cemented soil with 30% CWG								
	0	5	10	15	20	25	30	35	40
0.0	0	0	0	0	0	0	0	0	0
0.02	112	122	130	140	168	200	228	260	288
0.04	123	134	142	188	216	224	236	272	312
0.06	131	145	150	201	228	255	268	318	342
0.08	133	155	162	210	238	263	279	329	348
0.10	142	165	193	221	240	274	292	345	362

Table 10
Axial stress-strain behaviour of 40% CWG (%) and QDbGPC treated cemented soil.

Axial strain (%)	Axial stress (kN/m^2)								
	QDbGPC % by weight treated cemented soil with 40% CWG								
	0	5	10	15	20	25	30	35	40
0.0	0	0	0	0	0	0	0	0	0
0.02	115	125	134	142	170	202	231	264	294
0.04	125	136	145	191	218	226	239	276	318
0.06	134	148	152	204	230	258	271	323	346
0.08	138	158	164	215	241	267	283	331	353
0.10	144	170	198	225	242	276	298	348	365

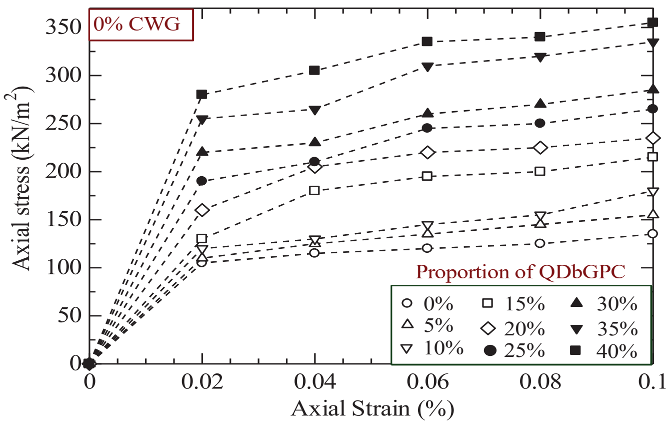

Fig. 4. Stress-strain behaviour of QDbGPC treated soil with 0% of CWG.

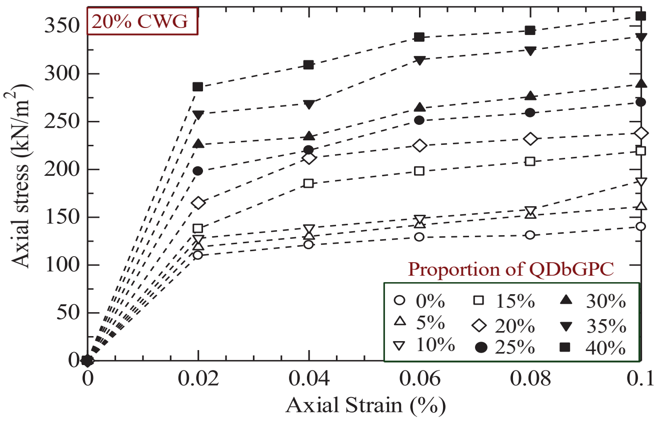

Fig. 6. Stress-strain behaviour of QDbGPC treated soil with 20% of CWG.

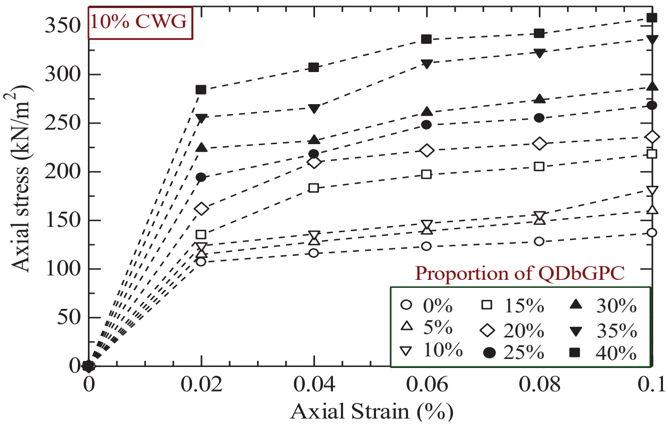

Fig. 5. Stress-strain behaviour of QDbGPC treated soil with 10% of CWG.

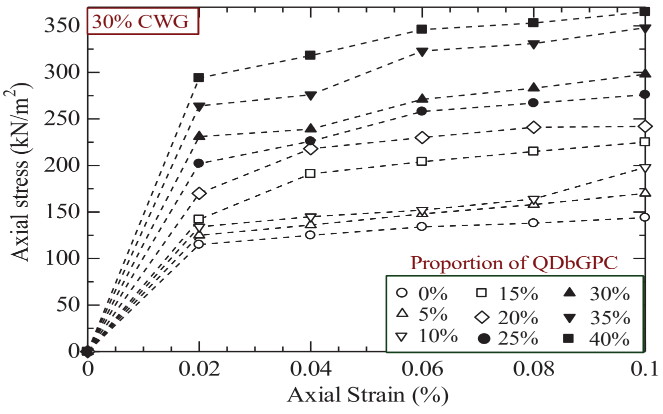

Fig. 7. Stress-strain behaviour of QDbGPC treated soil with 30% of CWG.

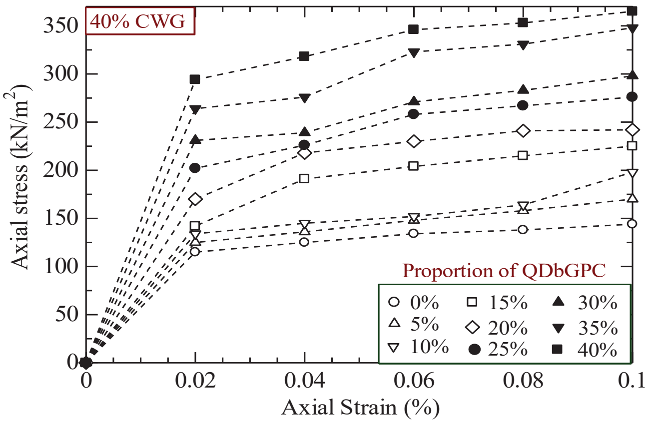

Fig. 8. Stress-strain behaviour of QDbGPC treated soil with 40% of CWG.

CWG presented in Figs. 4, 5, 6, 7 and 8 show a consistent pattern. It shows that the vertisol behaved in a similar pattern with the increased CWG. This is due to the physicochemical reactions and pozzolanic characteristics of the additives and to its ability to reduce adsorbed moisture and consequently making treated test soil with high clay composition to behave like granular matrix. The introduction of the additives filled the voids of the treated soil structure thereby improving the porosity of the matrix and however achieving a very stiff consistency. The cations released during the ion dissociation phase of the hydration and geopolymerization reactions of the treated soil improved the formation of stiff soil matrixes. This improvement satisfies the very stiff consistent requirement of between 150 kN/m^2 and 200 kN/m^2 for subgrade layer and between 200 kN/m^2 and 350 kN/m^2 for subbase layer in pavement construction [43].

4. Concluding Remarks

The following concluding remarks could be drawn from the foregoing; the shear characteristics were consistently improved with increased addition of both the quarry dust based geopolymer cement and the crushed waste glasses. The compaction behaviour i.e. the maximum dry density at optimum moisture content and density properties was also improved by the additives. The stress-strain relationship was also improved with the additives that the exercise achieved a very stiff consistency that satisfies the basic requirements for subgrade and subbase materials. The porosity, the poisson ratio and relative density of the treated soil were improved and they showed a consistent pattern. Important to note is the improvement recorded with the submerged density with the increased proportion of CWG and QDbGPC by weight, which showed that the treated soil can perform efficiently as a pavement material under a hydraulically bound environment.

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