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Structural analysis of consolidation settlement behaviour of soil treated with alternative cementing materials for foundation purposes

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Highlights

- Quarry dust (QD), crushed waste ceramics (CWC), and palm bunch ash (PBA) were obtained
- They were characterized to determine their aluminosilicate content and pozzolanic properties
- Test soil sample was studied to determine the preliminary properties
- CWC and PBA base GPC were synthesized for use as cementitious geopolymer additives
- The effect of QD, CWC and PBA on consolidation settlement of the treated soil was studied
- The effect of CWC base GPC on consolidation settlement of the treated soil was studied
- And the effect of PBA base GPC on consolidation settlement of the treated soil was also studied

Abstract

The structural analysis of the application of quarry dust (QD), crushed waste ceramics (CWC), palm bunch ash (PBA), crushed waste ceramics base geopolymer cement (CWCbGPC) and palm bunch ash base geopolymer cement (PBA bGPC) in the treatment of soil has been studied. The need to encourage the use of supplementary cementing materials in construction works is of great necessity. This is because of the further damage the emission of CO₂ is causing and its contribution to global warming. Laboratory experiments have been adopted to investigate the behaviour of test soil on the addition of admixtures. After the preliminary study, it was shown that the test soil was an A-7 soil according to AASHTO classification system and poorly graded soil of high clay content (GP/CH) according to the USCS. The treatment protocol was used to study the consolidation settlement (CS) of the treated test soil and results showed that the CS reduced steadily at the varied addition of the cementing additives. A more remarkable improvement was recorded with the geopolymer cements (GPC). The results equally showed that the PBA bGPC was observed to be better than the CWCbGPC in the treatment protocol. The exercise not only achieved the ridding the environment of solid wastes but showed that these waste materials could be reclaimed and synthesized into alternative cementing materials to replace ordinary Portland cement and remove its attendant CO₂ emission and the global warming effects from the atmosphere.

Keywords: Consolidation Settlement; Structural Analysis; Alternative Cementing Materials; Foundation Purpose; Solid Wastes; Geopolymer Cement.

1. INTRODUCTION

As the world moves away from an environment prone to the hazardous effects of carbon emission and global warming and into an ecofriendly environment, experts are making frantic efforts to key into the global movement (Onyelowe, 2017a; Olawale, 2013; Fedrigo et al. 2017). One of those events is the application of geopolymer cements synthesized from solid waste materials, for instance quarry dust (QD), crushed waste ceramics (CWC) and palm bunch ash (PBA). In recent times, geopolymer cement has proven to be a good replacement for the ordinary Portland cement in both concrete production and soil stabilization operations (Akbari et al. 2015; Ghosh et al. 2006;). Geotechnical and geoenvironmental experts have taken a step further in this technical direction by adapting the use of solid waste materials in the synthesis of geopolymer cements (GPCs) and using same in the stabilization of weak and expensive soils for pavement subgrade purposes and other geotechnical construction applications and needs (Davidovits, 2013). The QD, CWC and PBA having proven to contain excellent amount of aluminosilicate compounds, have been adapted as alternative cementing materials as both individual additives and coupled additives as in the case of CWC and PBA base geopolymer cements. Consolidation settlement (CS) is a structural phenomena peculiar with loaded soils especially the high clay content soils or the expansive soils. In pavement subgrade construction or placement, the degree of the consolidation settlement (CS) of the layer lateritic soil determines the extent of compaction passes in the field (Austroads, 2002). If the amount of consolidation settlement is high, greater compaction efforts and longer time are always needed to achieve a reliable soil maximum dry density. Soils with high amount of consolidation settlement can be treated with alternative cementing materials to reduce the amount consolidation settlement, hence reduce the compaction effort required to achieve densification, increase the soil maximum dry density and perhaps reduce the optimum moisture content at which this density is achieved. The application of blended QD, CWC, and PBA as individual additives and CWC and PBA base geopolymer cement, as coupled additives for the treatment of compacted soils was investigated in the present work. However, the preliminary properties of test soils and their behaviour with additives were studied with particular emphasis on; (i) the effect of QD, CWC and PBA addition on consolidation settlement of treated non-cemented lateritic soil, and (ii) the effect of CWC and PBA base GPC on consolidation settlement of treated non-cemented lateritic soils.

2. MATERIALS SELECTION AND EXPERIMENTAL PROGRAM

2.1 Materials Selection and Preparation

The test soil sample was collected from Ohia borrow pit at a depth of 2 meters. The test soil location map is presented in Fig.1. The disturbed sample was collected, tapped to remove lumps, open 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 at Afikpo, Ebonyi State, Nigeria. It was also open sundried and stored in silo bags for the laboratory exercise. Dangote Ordinary Portland Cement (DOPC) was purchased at Umuahia Timber market, Umuahia, Nigeria. Ground

Granulated Blast Furnace Slag (GGBFS)/Metallurgical Slag (MS) were collected from Delta Steel Company, Aladja, Warri, Nigeria. Crushed waste ceramics (CWC) and palm bunch ash (PBA) were collected from dump sites within Umuahia. These solid waste materials were sundried, crushed and burnt respectively and stored for use. The CWC and PBA based Geopolymer cements (GPCs) were 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 (Davidovits, 2013; Nikolov *et al.* 2017; Abdel-Gawwad and Abo-El-Enein, 2016; Hamidi *et al.* 2016; Akbari *et al.* 2015; Skvara *et al.* 2005 and Srinivasan and Sivakumar, 2013; Onyelowe and Okafor, 2015). According to the above research findings, the aluminosilicate materials needed in the synthesis of GPC are QD 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, which is the concentration needed to achieve an eco-friendly material. QD contains high concentration of aluminosilicates (Al-O-Si), has 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 CWC or PBA as the case may be in turn 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 amount of CO_2 emission into the atmosphere when ordinary Portland cement is produced under high energy consumptions. On the other hand, the atmosphere will eventually be set free of the solid wastes or byproducts of ceramic production and handling; CWC (Onyelowe, 2017a; 2017b; 2017c and 2017d), byproducts of metallurgical operations; GGBFS (MS), and the byproducts of rock quarrying operations; QD by their adaptation in the synthesis of GP cements and binders. The GP cement dry powder was stored for use as supplementary cementing material in the treated soil laboratory consolidation settlement investigation.

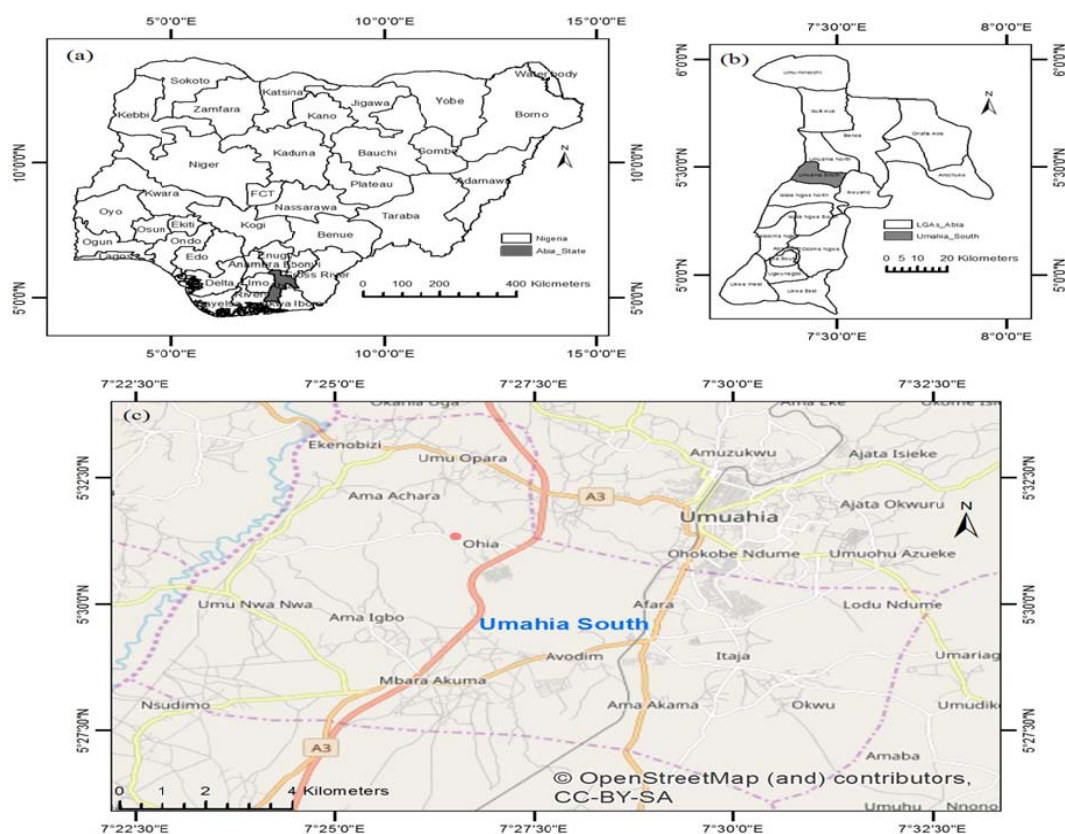


Figure 1 Test Soil Sample Location Map

2.2 Experimental Program

The general tests were conducted on the test soil for the purpose of identification and classification; (i) particle size distribution test was conducted with vertically arranged sieves of various sizes mounted on an automatic shaker in accordance with BS 1377-2 and Nigerian General Specification (BS 1924, 1990 and NGS, 1997).

(ii) Compaction Test with the Standard Proctor apparatus was conducted with 2016 ELE Automatic Compactor Machine in accordance with BS 1377-2 and Nigerian General Specification (BS 1377-2, 1990 and NGS, 1997).

(iii) the California Bearing Ratio Test (CBR) was also conducted with a 2015 S211 KIT CBR penetration machine, motorized 50kN used to load the penetration piston into the test 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 and NGS (BS 1377-2, 1990 and NGS, 1997).

(iv) Consistency Limits test was conducted using a 2013 cassagrande apparatus in accordance with BS 1377-2 and NGS (BS 1377-2, 1990 and NGS, 1997).

(v) Specific Gravity test was conducted by Pycnometer method on both the natural test soil and the treated soil in accordance with BS 1377-2, BS 1924 and NGS (BS 1377-2, 1990; BS 1924, 1990 and NGS, 1997).

(vi) And aluminosilicates, chemical oxides content and mineralogical content test was conducted on the test soils and the test materials with XRF method in accordance with BS 1377-2 and NGS (BS 1377-2, 1990 and NGS, 1997) and results were obtained.

(vii) Furthermore, consolidation test was extensively carried out on both the natural soil (control experiments) and the treated samples in accordance with BS 1377-2, BS 1377-6, BS 1924 and the Nigerian General Specification (BS 1377-2, 1990; BS 1377-6, 1990; BS 1924, 1990 and NGS, 1997). The test soil was prepared and treated with varying proportions of complementary cementing materials and composite or coupled polymer materials in the ratio of 1, 5, 10, 15, 20, 25, 30, 35, and 40% by weight of solid in a standard consolidation apparatus of 75 mm diameter and 20 mm thick. A total of 50 test samples were prepared for the five additive materials the test soil was treated with and subjected to test loading in turn in the one dimensional consolidation set up. This leaves test samples of cross section area equals 4418 mm². Each loading round lasted for 1 hour and results were observed. Equations 1, 2, 3 and 4 were used to estimate the relevant parameters (Smith and Smith, 1998).

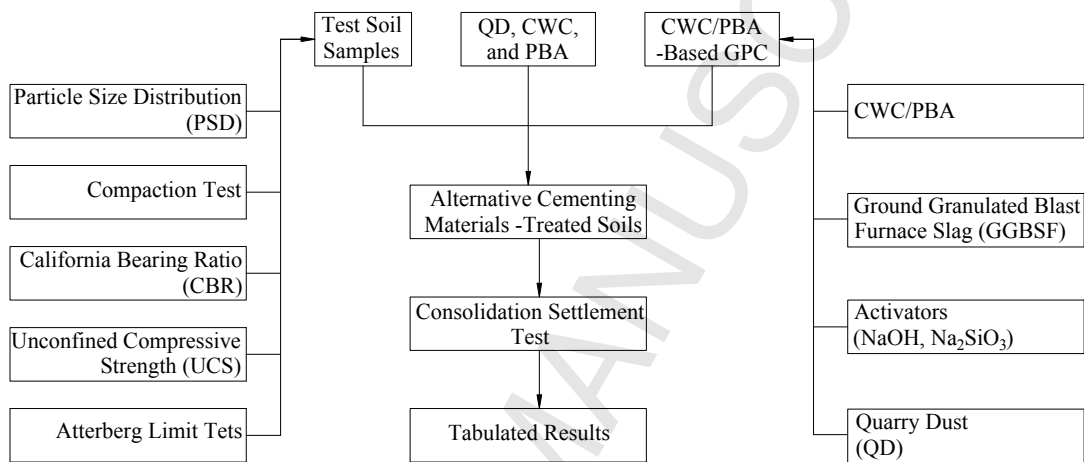


Figure 2 Schematic Presentation of the Experimental Program

$$H_s = \frac{M_s}{G_s \rho_w A} \quad (1)$$

$$e = \frac{H - H_s}{H_s} \quad (2)$$

$$m_v = \frac{dH}{H_1} \times \frac{1}{dP} \quad (3)$$

$$\rho_c = m_v H^* dP, (m) = m_v H^* dP * 1000, (mm) \quad (4)$$

Where;

M_s = mass of test sample after removing completely from consolidation apparatus at the end of test and drying in the oven

G_s = specific gravity of test sample

A = cross sectional area of test sample

ρ_w = unit weight of water = 1

H_s = equivalent height of solids

H = thickness of test sample

dH = change in test sample thickness at consolidation

H_1 = initial thickness of test sample prior to loading

e = void ratio of test sample

dP = change in pressure on test sample

m_v = coefficient of volume compressibility

ρ_c = One dimensional consolidation settlement

3. RESULTS AND DISCUSSION

3.1 Preliminary Remarks

The results of the experimental program were presented in tables and graphs in the subsequent pages. The test soil sample was investigated and characterized under the laboratory conditions with the basic tests results presented in Tables 1, and 2 and Fig. 3. The test results showed that the soil was classified as A-7 group soil according to the AASHTO classification method (AASHTO, 1993). It was also classified according to USCS as poorly graded sand and with clay content (GP/CH, SP-SC). It was also classified as highly plastic soil with plasticity index above 17% and expansive but with stiff consistency where UCS lies between 100 and 200kN/m² at 7 and 28 days curing (Gopal and Rao, 2011; Smith and Smith, 1998; Onyelowe and Agunwamba, 2012). Table 3 presents that the test materials have high aluminosilicate content and possess good pozzolanic properties (ASTM C618, 2014).

Table 1 Basic Properties of the Test Soil

Test Soil Properties/Unit	Test Results
% Passing BS No. 200 sieve	4.60
Natural Moisture Content, (%)	14
Liquid Limit, (%)	64
Plastic Limit, (%)	36

Plasticity Index, (%)	28
Coefficient of Curvature, $C_c = \frac{D_{30}^2}{D_{10} \times D_{60}}$	4.54
Coefficient of Uniformity, $C_u = \frac{D_{60}}{D_{10}}$	4.23
Specific Gravity	2.12
AASHTO/USCS	A-7/GP/CH
Condition/General Subgrade Rating	Poor
Optimum Moisture Content, (%)	13.13
Maximum Dry Density (g/cm^3)	1.80
California bearing ratio, (%)	8
Unconfined Compressive Strength (kN/m^2)	14 days 165
	7 days 125
Color	Ash

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	89	61	46	31	19	14	5	0
QD	100	89	44	23	18	15	14	12	5	2	0
CWC	100	98	89	70	65	55	42	37	22	18	0
GGBFS	100	96	82	76	63	54	47	39	24	19	0
PBA	-	-	100	98.27	74.1	52.15	41.67	22.56	9.18	0.49	0

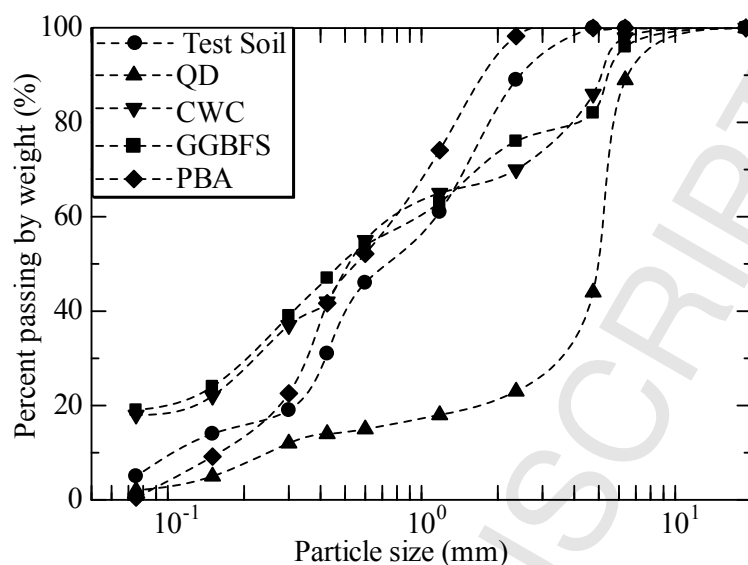


Figure 3 Grain size distributions of studied materials

Table 3 Oxides Composition of the materials used in this paper

Materials	Oxides Composition (content wt %)												Free CaO
	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	TiO ₂	LOI	P ₂ O ₅	SO ₃	IR	
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	-	-	-	-
CWC	63.45	4.14	12.11	1.23	0.78	1.09	0.01	1.78	1.89	0.71	0.11	-	0.03
GGBFS	33.45	12.34	42.10	0.05	11.45	-	-	-	0.21	-	-	-	0.40
PBA	60.96	15.49	14.59	0.45	0.40	-	0.81	Trace	5.81	-	-	-	0.64

*IR is Insoluble Residue; LOI is Loss on Ignition, PBA: Palm Bunch Ash

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

CWC: Crushed Waste Ceramics

3.2 The Effect of Cementing Additive Materials on Treated Test Soil

The effect of varied addition of QD, CWC, PBA, CWCbGPC and PBAbGPC on the deformation, void ratio, moisture content, specific gravity, and consolidation settlement of the treated test soil has been presented in Tables 4, 5, 6, 7, 8, 9, Figs. 4, 5, 6, 7, 8 and 9. The deformation of the quarry dust (QD) treated test soil reduced consistently with increased pressure and equally decreased with addition of varied percentages of quarry dust (QD). The rate of reduction from control to 1% addition of QD was 0.5% while the rate of reduction between 1% and 40% by weight QD of treated solid was 1%. The void ratio equally reduced with increased pressure in kN/m². This behaviour was consistent

with the varied addition of CWC and PBA to the treated soil. But the varied addition of blended CWCbGPC and PBAbGPC to the treated soil reduced the rate of deformation consistent between 1% and 40% with a remarkable reduction rate of about 2%. Mass of test sample after removing completely from consolidation apparatus at the end of test and drying in the oven, and specific gravity of test sample increased with increase in QD, CWC, PBA, CWCbGPC and PBAbGPC and the equivalent height of solids reduced with increase in the addition of the admixture materials. These parameters are the independent variables of the consolidation exercise upon which void ratio (e) and the consolidation settlement of the test samples depend. This behaviour could be due to the high pozzolanic effect of the additive materials, which consistently increased the specific gravity of the treated soil (Onyelowe and Bui Van, 2018; Arioiz et al. 2006). The materials may have served as fillers filling the void spaces hence achieving a densified matrix. Table 9 and Fig. 9 presented the effect the supplementary cementing materials on the consolidation settlement of the treated soil. At the varied addition of between 1% and 20% QD by weight, the CS decreased at the rate of between 20% and 33.3% while it remained steady beyond 20% and to 40% QD by weight. A similar behaviour was observed with addition of CWC but it became steady beyond 10% CWC by weight and to till 40%. It would have been similar with the addition of PBA but there was inconsistent increase and decrease with this treatment. The CS reduced with the addition of PBA till 20% addition, was steady to 25%, reduced again at 30%, increased again at 35% and remained steady till the 40% PBA by weight. But the behaviour of the CS with the geopolymer cements was very similar. The addition of the geopolymer cements consistently reduced the CS of the treated soil but changed at 30% CWCbGPC and 25% PBAbGPC where the CS increased by a rate of 50% at those points, where it is evident that CWCbGPC and PBAbGPC should not be used beyond 30% and 25% respectively. Generally, QD and PBA seem to be more reliable cementing materials. While CWCbGPC and PBAbGPC are geopolymer cements, PBAbGPC proved to be more reliable too because it provided a more consistent treatment in terms of the behaviour of the consolidation settlement of the treated soil. This behaviour may have been due to the presence of increased calcium ion from the metallurgical slag, which was a component in the synthesis of the geopolymer cement (Smith and Smith, 1998; Meegoda and Ratanweera, 1994; Gidigasu and Dogbey, 1980; Hariz et al. 2017). This enhanced solidification of the treated matrix at room temperature. At reduced CS, the cementation, stiffening, densification, flocculation, and stabilization of the treated soil would be achieved at reduced compaction effort and reduced pore moisture expulsion as presented in Fig. 9 because there may be left a much reduced degree of deformation beyond which consolidation settlement ends (Acar and Oliviera, 1990; Gopal and Rao, 2011).

Table 4 Consolidation properties behaviour of QD treated test soil

Pressure P (kN/m ²)	Thickness of QD (%) treated test sample after consolidation, H (mm)										Void ratio of QD treated test sample at consolidation, e																			
	0	1	5	10	15	20	25	30	35	40	0	1	5	10	15	20	25	30	35	40										
0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	0.46	0.54	0.61	0.74	0.93	1.02	1.15	1.32	1.47	1.59
50	19.8	19.7	19.4	19.2	19.0	18.8	18.6	18.4	18.2	17.9	18.4	18.2	17.9	18.2	17.9	18.4	18.2	17.9	18.2	17.9	0.44	0.52	0.56	0.67	0.84	0.90	1.00	1.14	1.25	1.32
100	19.6	19.5	19.2	19.0	18.8	18.6	18.4	18.2	18.0	17.8	18.4	18.2	18.0	17.8	18.4	18.2	17.8	18.4	18.2	17.8	0.43	0.5	0.55	0.65	0.82	0.88	0.98	1.11	1.22	1.31
150	19.4	19.3	19.1	18.9	18.7	18.5	18.3	18.1	17.9	17.7	18.5	18.3	18.1	17.9	17.7	18.5	18.3	18.1	17.9	17.7	0.41	0.49	0.54	0.64	0.81	0.87	0.97	1.10	1.21	1.30
200	19.15	18.9	18.7	18.6	18.5	18.3	18.1	17.9	17.7	17.5	18.3	18.1	17.9	17.7	17.5	18.3	18.1	17.9	17.7	17.5	0.4	0.46	0.51	0.62	0.79	0.85	0.95	1.08	1.18	1.27
250	19.0	18.8	18.6	18.4	18.2	18.1	18.0	17.8	17.6	17.4	18.2	18.0	17.8	17.6	17.4	18.2	18.0	17.8	17.6	17.4	0.38	0.45	0.5	0.60	0.76	0.83	0.94	1.07	1.17	1.26
300	18.8	18.7	18.4	18.2	18.0	17.8	17.6	17.4	17.3	17.2	18.0	17.8	17.6	17.5	17.3	17.2	18.0	17.8	17.6	17.4	0.37	0.44	0.48	0.58	0.74	0.80	0.89	1.03	1.13	1.23
350	18.7	18.6	18.3	18.1	17.8	17.6	17.4	17.3	17.1	17.0	17.8	17.6	17.4	17.3	17.1	17.0	17.8	17.6	17.4	17.2	0.36	0.43	0.47	0.57	0.72	0.78	0.87	1.01	1.11	1.21
400	18.5	18.4	18.1	17.9	17.7	17.5	17.3	17.1	17.0	16.8	17.5	17.3	17.1	17.0	16.8	16.8	17.5	17.3	17.1	16.8	0.35	0.42	0.46	0.55	0.71	0.77	0.86	0.99	1.10	1.18
450	18.3	18.2	18.0	17.8	17.6	17.4	17.2	17.0	16.9	16.7	17.4	17.2	17.0	16.9	16.7	16.7	17.4	17.2	17.0	16.7	0.33	0.4	0.45	0.55	0.70	0.76	0.85	0.97	1.09	1.17
500	18.1	18.0	17.8	17.6	17.4	17.2	17.1	16.9	16.7	16.5	17.4	17.2	17.1	16.9	16.7	16.5	17.4	17.2	17.1	16.5	0.32	0.39	0.43	0.53	0.68	0.74	0.84	0.96	1.06	1.14
550	17.9	17.8	17.6	17.4	17.2	17.0	16.8	16.6	16.4	16.2	17.4	17.2	17.0	16.8	16.6	16.2	17.4	17.2	17.0	16.2	0.3	0.37	0.42	0.51	0.66	0.72	0.81	0.93	1.02	1.10
600	17.7	17.6	17.4	17.2	17.0	16.8	16.6	16.3	16.1	16.0	17.4	17.2	17.0	16.8	16.6	16.0	17.4	17.2	17.0	16.0	0.29	0.36	0.4	0.49	0.64	0.70	0.79	0.89	0.99	1.08
650	17.6	17.5	17.3	17.1	16.9	16.7	16.5	16.3	16.1	15.9	17.4	17.2	17.0	16.8	16.6	15.9	17.4	17.2	17.0	15.9	0.28	0.35	0.39	0.49	0.63	0.69	0.78	0.89	0.99	1.06
700	17.4	17.3	17.1	16.9	16.7	16.5	16.3	16.0	15.8	15.6	17.4	17.2	17.0	16.8	16.6	15.6	17.4	17.2	17.0	15.6	0.27	0.33	0.38	0.47	0.62	0.67	0.75	0.86	0.95	1.02
M_s (g)	128.5	128.9	129.5	130.2	131.1	131.8	132.6	133.1	133.9	134.5	131.1	131.8	132.6	133.1	133.9	134.5	131.1	131.8	132.6	133.1	133.9	134.5	131.1	131.8	132.6	133.1	133.9	134.5	Mass of test sample after removing completely from consolidation apparatus at the end of test and drying in the oven, specific gravity of sample and equivalent height of solids are the independent variable the consolidation exercise upon which void ratio (e) of the test sampl	
G_s	2.12	2.25	2.36	2.56	2.87	3.02	3.23	3.50	3.74	3.95	3.02	3.23	3.50	3.74	3.95	3.02	3.23	3.50	3.74	3.95	3.02	3.23	3.50	3.74	3.95	3.02	3.23	3.50	depend.	
H_s (mm)	13.7	13.0	12.4	11.5	10.3	9.9	9.3	8.6	8.1	7.7	10.3	9.9	9.3	8.6	8.1	7.7	10.3	9.9	9.3	8.6	8.1	7.7	10.3	9.9	9.3	8.6	8.1	7.7		

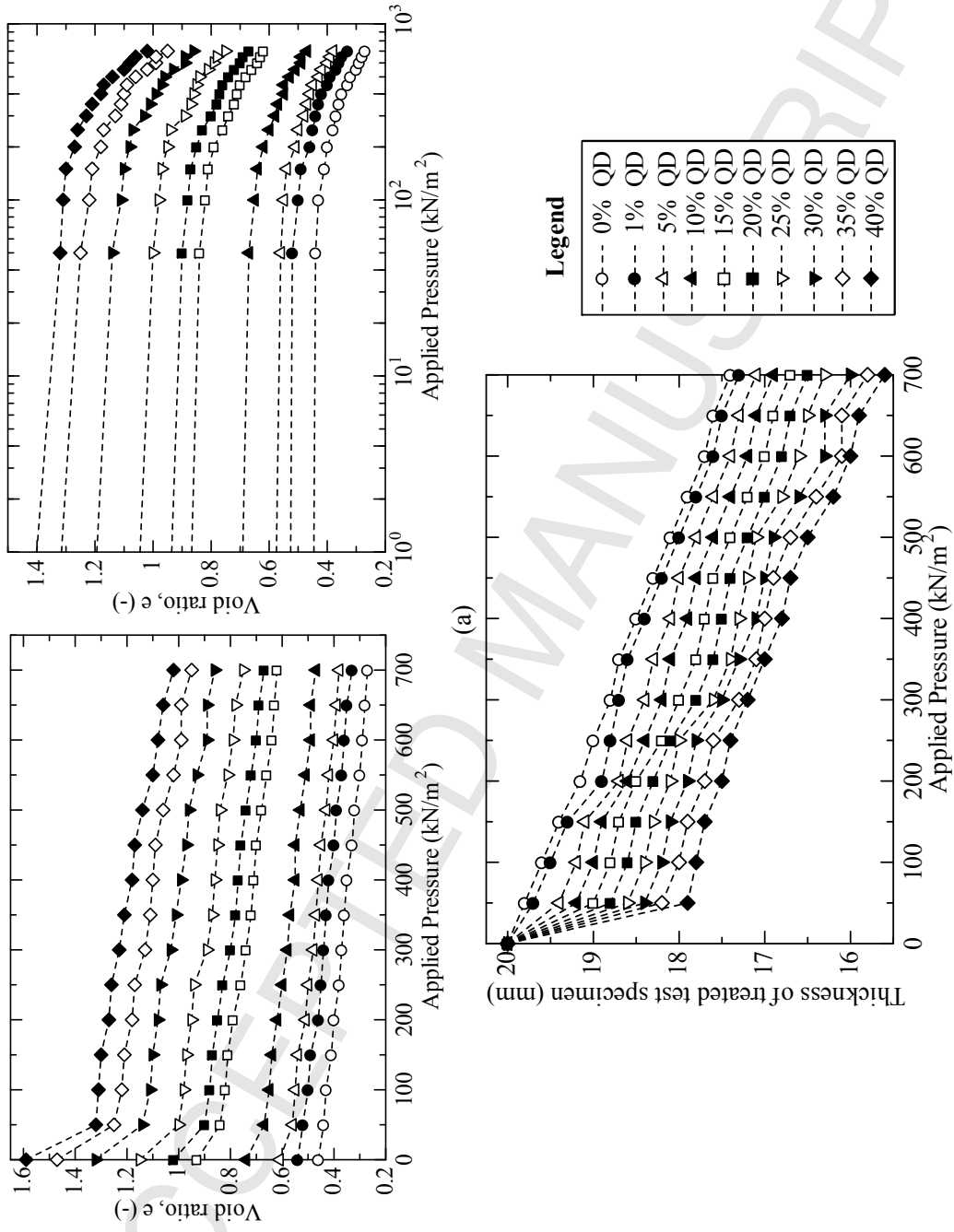


Figure 4 Consolidation properties behaviour of QD treated test soil: void ratio (a), (b) thickness of treated sample

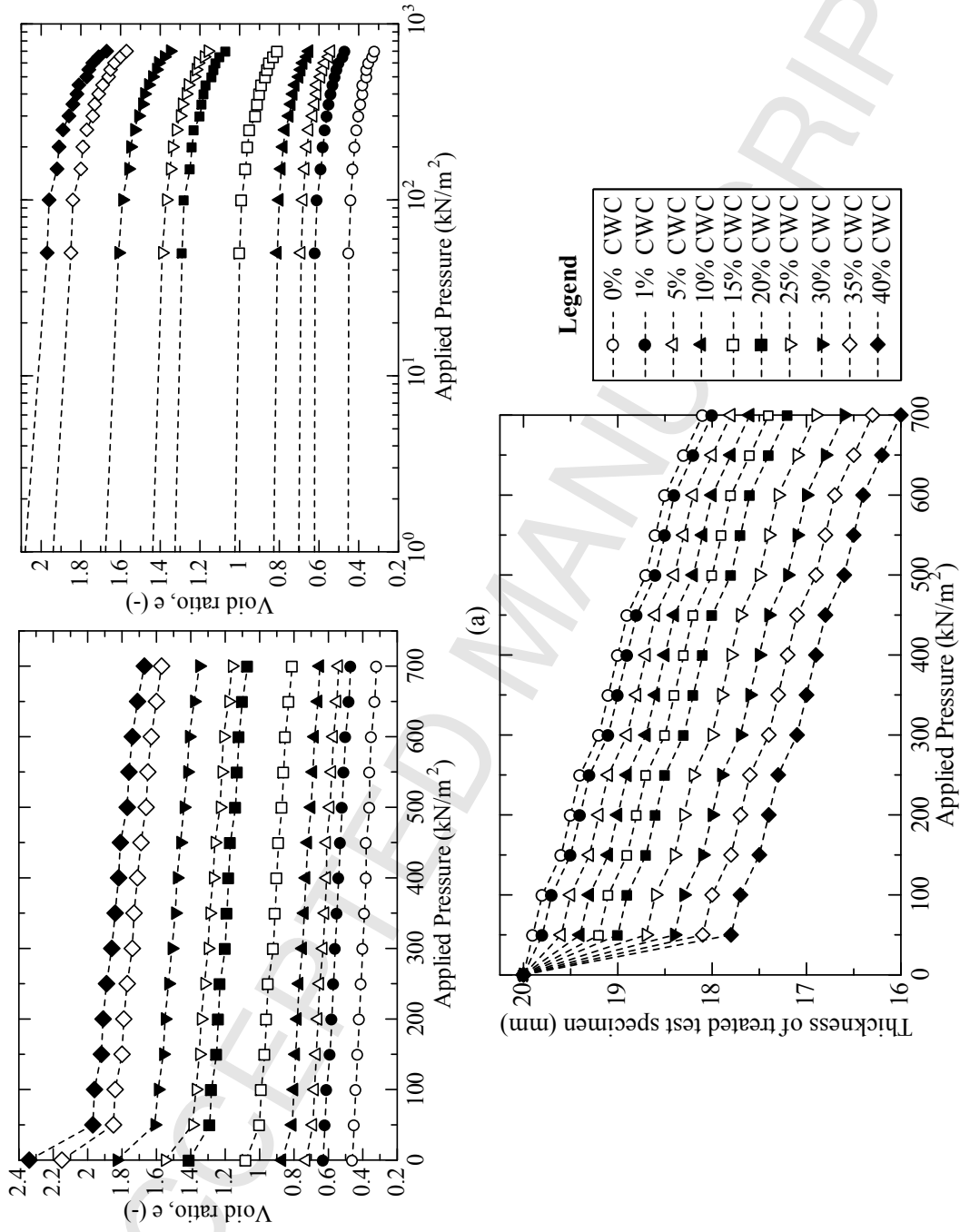


Figure 5 Consolidation properties behaviour of CWC treated test soil: void ratio (a), (b) thickness of treated sample

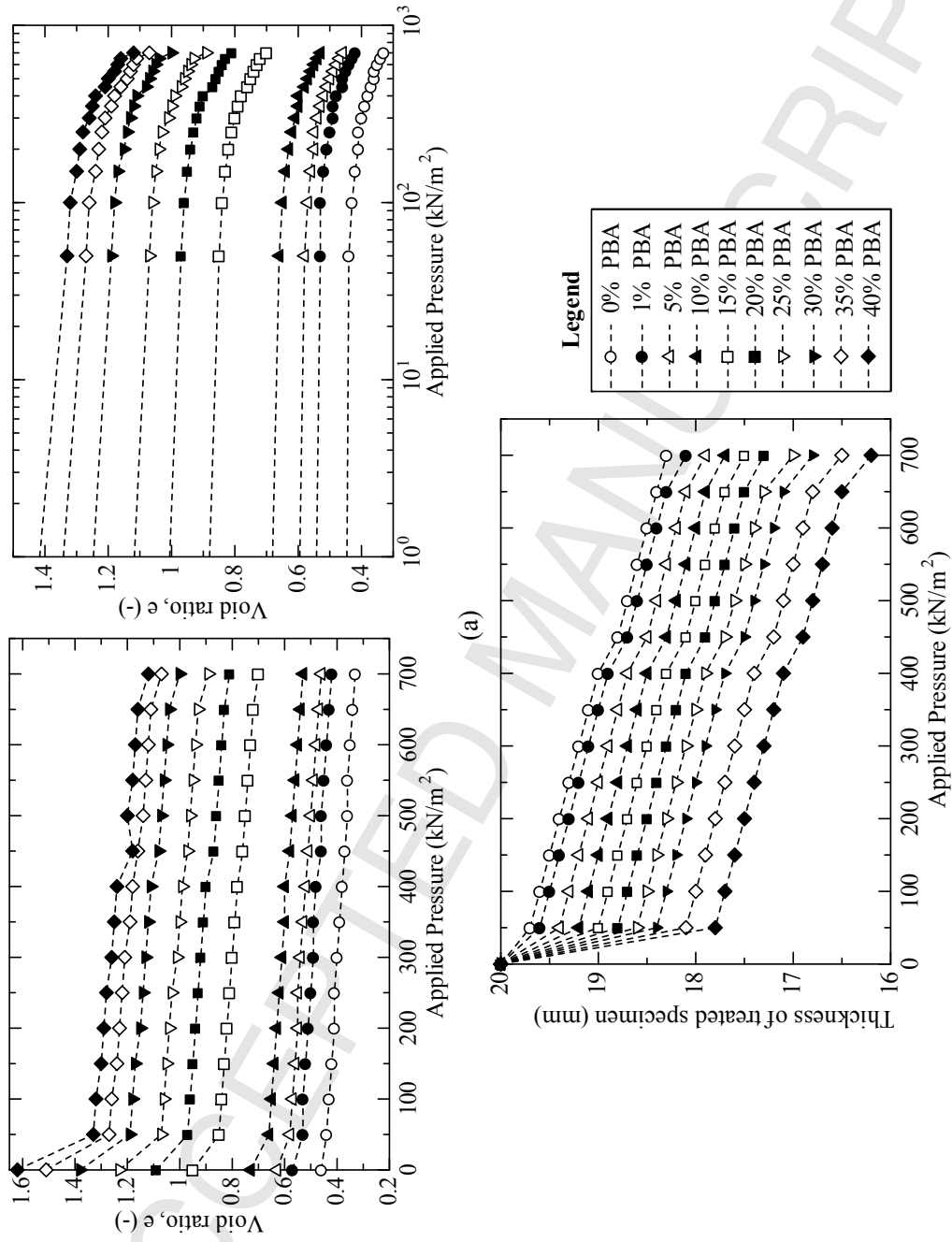


Figure 6 Consolidation properties behaviour of PBA treated test soil: void ratio (a), (b) thickness of treated sample

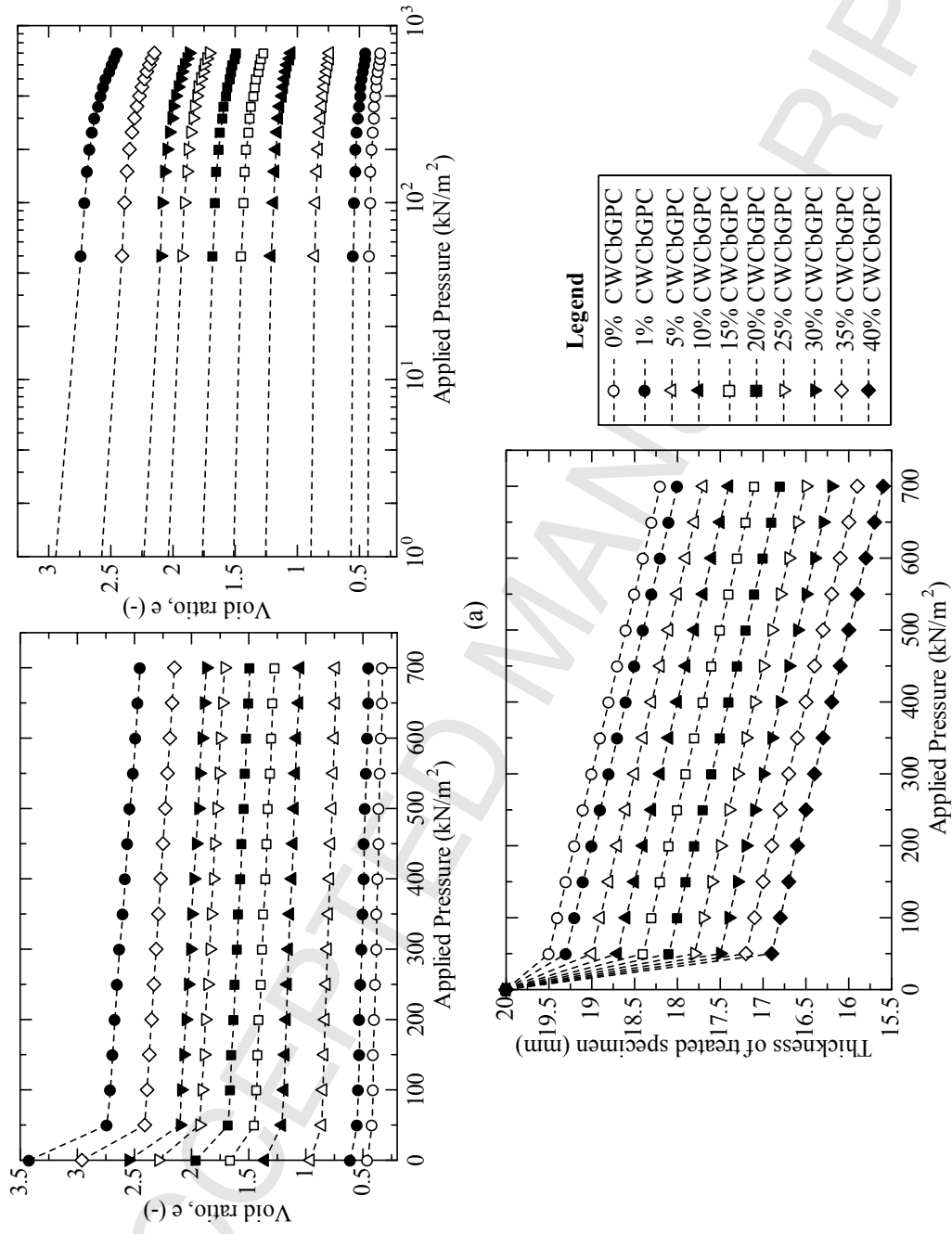


Figure 7 Consolidation properties behaviour of CWCbGPC treated test soil: void ratio (a), (b) thickness of treated sample

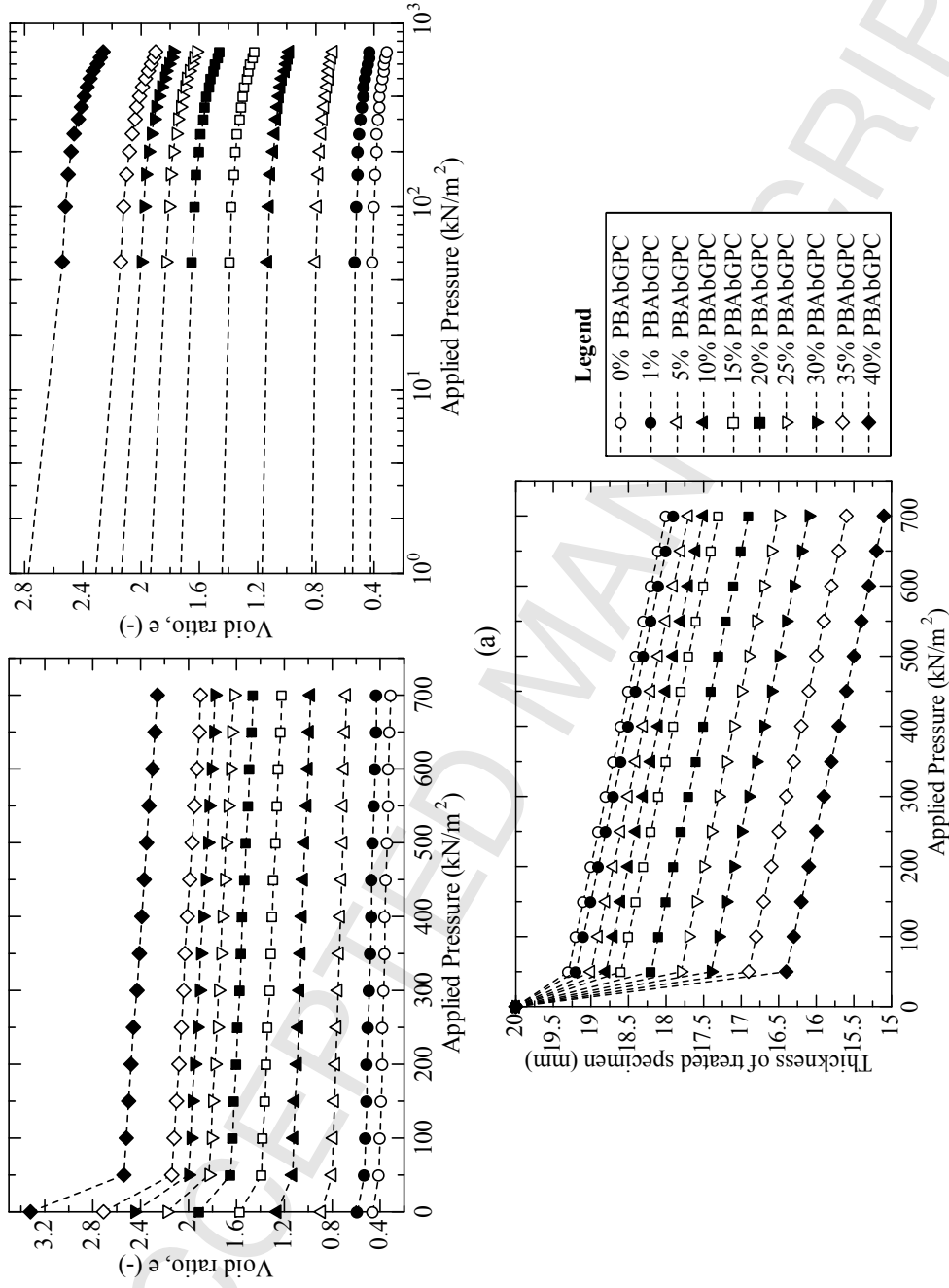


Figure 8 Consolidation properties behaviour of PBAbGPC treated soil: void ratio (a), (b) thickness of treated sample

Table 9 Consolidation settlement of alternative cementing materials treated test soil

Cementing Additive	QD			CWC			PBA			CWCbGPC			PBAbGPC			
	G_s	w (%)	m_v	ρ_c (mm)	G_s	w (%)	m_v	ρ_c (mm)	G_s	w (%)	m_v	ρ_c (mm)	G_s	w (%)	m_v	ρ_c (mm)
0	2.12	13.1	0.06	120	2.12	13.1	0.04	80	2.12	13.1	0.06	120	2.12	13.1	0.03	60
1	2.25	12.5	0.06	120	2.38	12.2	0.04	80	2.28	12.3	0.06	120	2.34	12.0	0.03	60
5	2.36	11.2	0.05	100	2.55	11.0	0.03	60	2.38	11.1	0.05	100	2.86	10.8	0.03	60
10	2.56	10.4	0.04	80	2.78	10.2	0.02	40	2.54	10.3	0.04	80	3.45	10.0	0.02	40
15	2.87	9.8	0.03	60	3.12	9.4	0.02	40	2.88	9.6	0.03	60	3.90	9.2	0.01	20
20	3.02	9.2	0.02	40	3.65	9.0	0.02	40	3.12	9.1	0.02	40	4.35	8.8	0.01	20
25	3.23	8.4	0.02	40	3.89	8.2	0.03	60	3.33	8.3	0.02	40	4.85	8.0	0.01	20
30	3.50	8.0	0.02	40	4.34	7.7	0.04	80	3.58	7.8	0.01	20	5.25	7.5	0.02	40
35	3.74	7.5	0.02	40	4.86	7.3	0.04	80	3.79	7.4	0.02	40	5.88	7.1	0.01	20
40	3.95	7.0	0.02	40	5.20	7.0	0.04	80	3.97	7.0	0.02	40	6.58	6.8	0.01	20

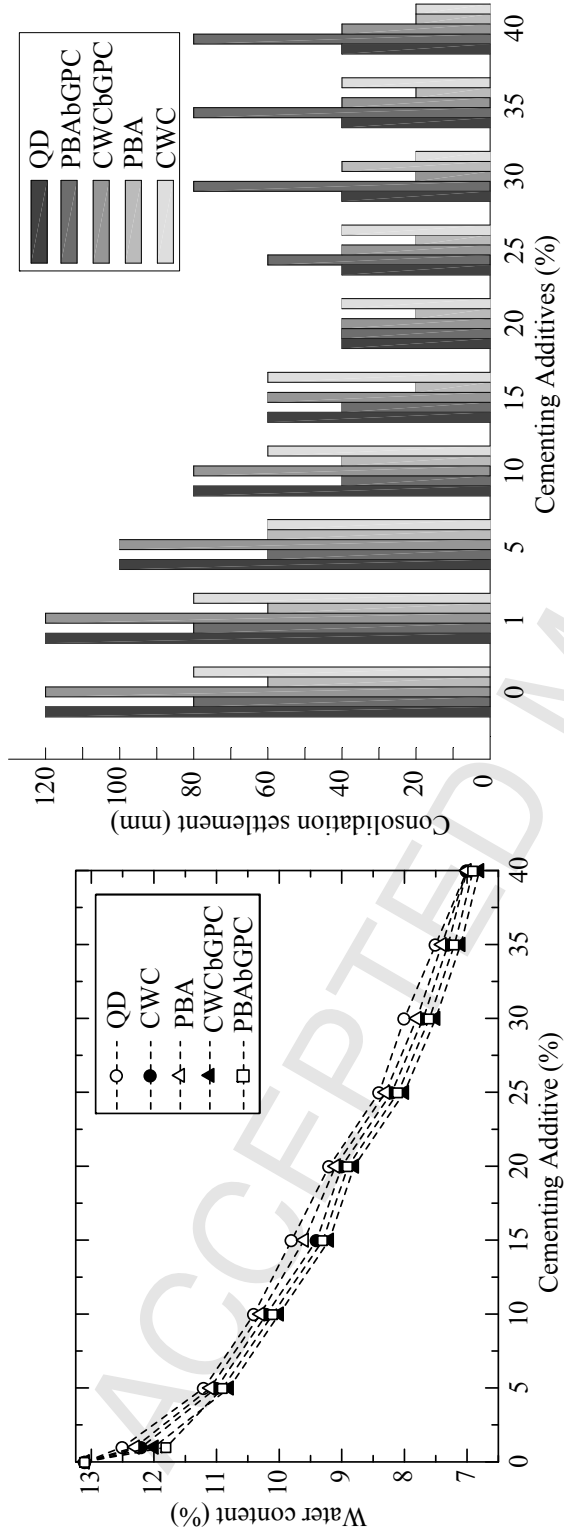


Figure 9 Consolidation settlement of alternative cementing materials treated test soil

4. CONCLUDING REMARKS

Taking into consideration the results of the laboratory exercises conducted on the test soil which was treated with QD, CWC, PBA, CWCbGPC and PBAbGPC, it can be concluded with the following remarks;

- (a) The test soil was tested for the preliminary parameters and results showed that it was classified as A-7 group soil according to AASHTO classification system and GP/CH according to USCS; it was also classified as a highly plastic soil with plasticity index above 17% and consequently as an expansive soil.
- (b) The CWC base GPC and PBAbGPC were synthesized in accordance with the conditions suggested by previous research findings (Davidovits, 2013), were used as coupled materials and QD, CWC, and PBA were used as individual cementing additives to treat the test soil under the laboratory conditions and was added in the proportions of 1, 5, 10, 15, 20, 25, 30, 35 and 40% to determine consolidation settlement behavior of the treated soil.
- (c) The GPC were produced under alkali activated conditions and the alkali-activated ($\text{NaOH} + \text{Na}_2\text{SiO}_3$) cement produced under dry condition provided the possibility to adapt solid 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 cementing additive treated soil demonstrated significant and consistent reduction in consolidation settlement with the GPC showing to be better. 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 consolidation settlement handling management abilities, high temperature resistance of above 600°C , resistant to acid, salts and sulfate attacks, and resistant to brittle and corrosion effects. This behavior may be attributed to the properties of the constituent elements of the GPC where GGBFS produces high level of calcium and QD produces high concentration of aluminosilicates, which contribute to density gain by calcinations, cation exchange, hydration reactions and polycondensation.

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