Experimental assessment of subgrade stiffness of lateritic soils treated with crushed waste plastics and ceramics for pavement foundation

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Abstract

The assessment of subgrade stiffness of four test soils treated with crushed waste ceramics (CWC) and crushed waste plastics (CWP) has been experimented on under laboratory conditions. There have been recorded failures of pavements resulting from inadequate subgrade formations and the use of weak and expansive soils as subgrade materials. The changes in the behavior of these foundation materials affect the performance and overall behavior of the entire pavement or foundation structure. The aim of this work was to assess the behavior of test soils commonly used as subgrade materials and treat same with selected solid waste based geomaterials to enhance their ability to withstand dynamic and cyclic loads. The selected solid waste based geomaterials were crushed waste ceramic and crushed waste plastics. The test materials including the soils were tested for characterization procedure. The preliminary test results showed that the test soils were classified as A-2-7, A-2-6, A-7 and A-7-5, respectively according to AASHTO classification system and poorly graded soils according to USCS. They were also classified as highly plastic soils and expansive with plasticity indexes of above 17%. The oxide composition test on the CWC and CWP shows that the materials possess pozzolanic properties with high aluminosilicates. The test soils were treated with these geomaterials in the proportion of 10% to 120% by weight. The treatment protocol showed that the CBR, resilient modulus, and *r*-value improved consistently with increased CWC and CWP. Lateral deformation observed from the modified triaxial compression also reduced consistently with increased proportions of CWC and CWP. It is novel to have achieved improved California bearing ratio characteristics, resilient modulus, resistance value and lateral deformation properties of the test soils with a solid waste based geomaterial. It is also promising that beyond

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the proportion utilized in the laboratory, the CWC and CWP treated soils will resist both axial and lateral deformation or failure when compacted to the maximum dry density and optimum moisture.

Keywords: subgrade stiffness; crushed waste plastics; crushed waste ceramics; moisture bound materials; recycled solid waste materials; geomaterials

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1 INTRODUCTION

The utilization of recycled solid waste materials in crushed or amorphous forms as geomaterials has been proven technically reliable in the field of Geotechnical and Pavement Materials Engineering [1–19]. Various waste materials have been in use in the treatment or stabilization procedure to improve the physical, mechanical, structural and geotechnical properties or characteristics of expansive test soils [7–34]. Palm bunch ash, palm kernel shell ash, bagasse ash, periwinkle shell ash, paper ash, egg shell ash, rice husk ash, etc. gotten by the direct combustion of the parent solid waste materials have been utilized in various ways and proportions to stabilize expansive soils for the purpose of foundation constructions [23–34]. Results from these experimental protocols and exercises have shown that the test soils properties improved and satisfied basic construction requirements. Crushed oyster shells, crushed snail shell, crushed periwinkle shells, etc. have equally being used to stabilized test soils. These crushed solid waste materials though biodegradable materials, exhibit pozzolanic properties that enhance their bonding strength with the treated soils hence improve their properties [23–41]. In the case of ash materials, they exhibit amorphous and pozzolanic properties [42–44]. This makes them fit into the reactions that take place in the adsorbed complex or the double diffused layer interface where hydration, ions dissociation, calcinations, polymerization or geopolymerization, and cation exchange reactions take place. And by these processes, the formation of floccs within the treated blend is improved and eventual densification [23–34, 44–53]. This is an important factor responsible for the subgrade stiffness of the treated soils [54]. It is unfortunate that research in recent years rely only on the results of the California bearing ratio test on treated soils to establish the subgrade stiffness and strength [54, 55]. But subgrade stiffness is the ability of treated and untreated soils to withstand shear and lateral displacement failures (deformation). For this purpose, the use of a modified Resilient Modulus test and Resistance Value (*R*-value) test were supported to the results of the California ratio test [4, 5, 56–61]. Test materials resistance to lateral deformation is expressed as *R*-value. This procedure is a modified triaxial compression test where a stabilometer is adapted to determine the *R*-value of foundation materials. Resilient modulus is the elastic modulus of a test materials based on recoverable elastic strain subjected to repeated load [4, 5, 56–61]. These were to determine both the shear deformation behavior and lateral deformation behavior of the treated test soils [4, 5, 56–61]. This is achieved in this work by the utilization of crushed waste plastics and crushed waste ceramics [62–64]. Plastics and ceramics are industrial products of polymerization and geopolymerization reactions, which possess elastoplastic properties [62–64]. The discharge of waste from these products as household solid wastes and scrap losses from poor handling has been an environmental problem in the developing countries [62–64]. These are recycled to serve various purposes, which included their utilization as geomaterials. Chemical oxides composition investigation has shown that these materials contain high level of aluminosilicates. These compounds are responsible for the stabilization reactions and geochemistry between test soils and admixtures. The utilization of crushed waste plastics and crushed waste ceramics to improve the subgrade stiffness properties of lateritic soils is the main aim of this work with particular emphasis on; (i) effect of the crushed waste plastics and crushed waste ceramics on the California bearing ratio characteristics, (ii) effect of the crushed waste plastics and crushed waste ceramics on the deviatoric stress and resilient modulus of the treated test soils and (iii) effect of the crushed waste plastics and crushed waste ceramics on the R-Value of the treated test soils.

2 MATERIALS AND METHODS

2.1 Materials preparation and sampling

Four different soil samples were collected from for different sources of engineering soils for the purpose of pavement construction in Abia State and other neighboring states. These borrow pits are located in Olokoro, Amaba, Ohiya and Akwete respectively. These are found on coordinates 5°29′16″ North and 7°28′58″ East (Olokoro location), 5°27′0″ North and 7°31′60″ East (Amaba location), and 5°31′0″ North and 7°26′0″ East (Ohiya location) and 4°53′14″ North and 7°21′26″ (Akwete location). The samples were sundried for one week, 200 g each was measured and kept in bags for use. The waste plastics and ceramics were collected from dumpsites within Umuahia municipal, sundried and crushed. Ordinary Portland cement was purchased from Umuahia Modern Timber Market that meets the requirements of ASTM C618 [42]. The preliminary characterization exercises were conducted on the test materials to determine their gradation and chemical oxide composition

Table 1. *Basic properties of test soils.*

Property description of test soils and units	Values			
	Test soil (A)	Test soil (B)	Test soil (C)	Test soil (D)
% Passing Sieve No 200	2.85	10	4.6	7.6
NMC (%)	12.1	13.49	14	16
LL (%)	40	46	64	65
PL (%)	18	21	36	33
PI (%)	22	25	28	32
SL (%)	8	8	7	10
FSI (%)	250	234	275	296
G_s	2.6	2.43	2.12	2.08
AASHTO Classification	A-2-7	A-2-6	A-7	A-7-5
USCS	GP, CH	GP	GP, CH	GP, CH
MDD (g/cm^3)	1.76	1.85	1.80	1.56
OMC (%)	13.1	16.2	13.13	15.4
CBR (%)	12	13	8	7
R-Value	11.74	11.70	11.70	11.50
M_R (kN/m^2)	0.42E+05	0.42E+05	0.42E+05	0.72E+05
Color	Reddish Brown	Reddish Gray	Reddish Ash	Ash

(aluminosilicates content). These test admixtures were utilized in the percentages of 10–120% in an incremental rate of 10% to treat the soils.

2.2 Experimental program

Various preliminary experimental programs were conducted at different phases of this exercise. The particle size analysis, compaction, Atterberg shrinkage limits, free swell index, and specific gravity were generally conducted on the test soils in accordance with BS 1377 [56]. This was carried out to determine the basic properties of the test soils. Similarly, chemical oxide composition and particle size distribution tests were conducted to determine the aluminosilicate content and gradation, respectively in accordance with ASTM C618 [42] and BS 1377 [56], respectively. Atterberg limits and compaction tests were also carried out on the test soils treated with crushed waste ceramics (CWC) and crushed waste plastics (CWP) in accordance with BS 1924 [43] to determine the effect of these recycled solid waste materials on the consistency and compaction characteristics of the treated soils. The California bearing ratio of the treated soils was also conducted in accordance with BS 1924 [43]. Of particular interest to this work was the stiffness of the treated soils as subgrade or pavement materials, which was determined with the resilient modulus and resistance value (*r*-value) test carried out on the CWC and CWP treated soils in accordance with AASHTO [58, 59], AASHTO T 307 [5], AASHTO T 190-09 [4], and ASTM D 2844-01 [57]. Specifically, the resilient modulus of both the control specimen and treated test soils was determined under the laboratory conditions. This represented the simulated physical and stress conditions of geomaterials treated soils A, B, C and D overlain by flexible pavements subjected to dynamic traffic loads. A cyclic axial stress of fixed magnitude under deviatoric stress, load duration of 0.1 s, and cyclic duration of 3 s is applied to prepared cylindrical test specimens in a modified triaxial compression set up. The final recoverable axial deformation response (recoverable strain) and the deviatoric stress of the test specimens were measure and the resilient moduli at different proportions of the additives were determined with Equation (1). The resistance *r*-value test adapted was of the Hveem–Carmany procedure for testing both treated and untreated compacted soils with the stabilometer adapted into the modified triaxial compression test set up. This presents results of the material performance when utilized as subgrade, subbase or base materials of a pavement subjected cyclic traffic loading. The different blends of the soil-additive mix were thoroughly mixed with the amount of moisture to equal one-half to two-thirds of the total needed to achieve a saturated mixture. The specimens are placed in an enclosed container for 12 hours. Before compaction, the blends were mixed with the final portion of moisture necessary to attain saturation. A total of 247 specimens for each test soil were prepared to determine the lateral displacement (D) under applied cyclic axial loads (vertical and horizontal loads). The resistance values (R) were determined with Equation (2). Ordinary Portland cement was utilized at constant proportion of 2.5% by weight.

Table 2. *Particle size distribution 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
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
Soil D	-	-	100	92	76	67	49	32	19	8	0
CWC	100	97	86	70	55	45	33	28	25	21	0
CWP	100	92	84	75	65	55	43	36	21	16	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
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	-	-	-	-	-	-
Soil D	72.34	17.30	5.40	2.32	0.34	2.13	0.17	-	-	-	-	-	-
CWC	64.45	24.14	0.25	1.3	0.28	3.69	2.51	0.18	1.09	-	2.11	-	-
DOPC	21.45	4.45	63.81	3.07	2.42	0.83	0.20	0.22	0.81	0.11	2.46	0.16	0.64

*IR is insoluble residue, LOI is loss on ignition, CWC: crushed waste ceramics; DOPC: Dangote Ordinary Portland cement.

$$M_R = \frac{\rho_d}{\varepsilon_r} \tag{1}$$

$$R = 100 - \left\{ \frac{100}{\left(\frac{2.5}{D}\right)\left[\left(\frac{P_v}{P_h}\right) - 1\right] + 1} \right\} \tag{2}$$

where; M_R = resilient modulus, ρ_d = deviatoric stress, ε_r = strain, R = resistance value (R-value), D = lateral deformation or displacement of subgrade material, P_v = vertical pressure, P_h = horizontal or cell pressure.

3 RESULTS AND DISCUSSIONS

3.1 General test materials characteristics

The basic properties of the test soils are presented in Tables 1–3 and Figures 1 and 2. The test soil was observed to possess 2.85%, 10%, 4.6% and 7.6% passing sieve No. 200, and classified as A-2-7, A-2-6, A-7 and A-7-5, respectively, according to AASHTO classification method. Test soils A, C and D were also classified as poorly graded with high clay content while test soil B was classified as poorly graded according to unified soil classification system. The results of the consistency protocol show that the test soils are highly plastic soils (>17%) with high free swell index. The basic results of the resistance *r* value indicate that the test soils are sandy clay group (10–20) while that of the resilient modulus shows that the soils fall under clayey subgrade (0.345E+05 to 1.034E+05 kN/m^2) [61]. The chemical oxides composition test results presented in Table 3 and Figure 2 show that the test materials possess high aluminosilicates responsible for the pozzolanic, calcination and hydration reactions that take place in a stabilization process.

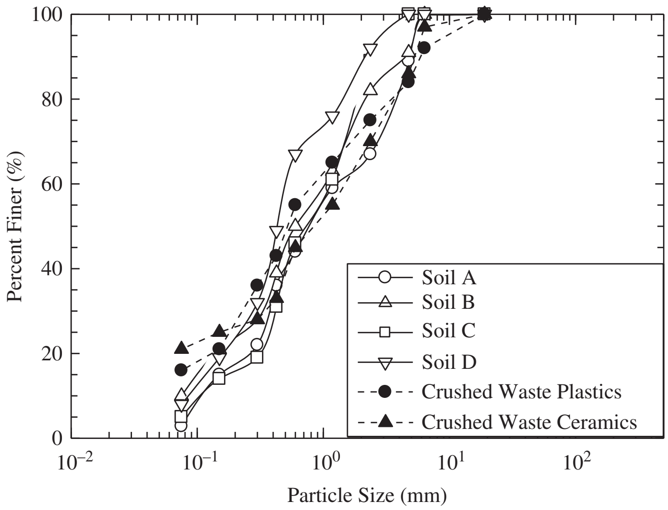

Figure 1. *Grain size distribution of studied materials.*

3.2 Effects of crushed waste ceramics on behavior of treated soils

3.2.1 *Consistency limits behavior*

Consistency behavior of 2.5% DOPC and varying proportions of CWC treated test soils was presented in Figure 3. Preliminary results had shown that the test soils were classified as highly plastic soils with high clay content responsible for the change in volume by swelling and shrinkage under the influence of moisture. This property in effect shows that the soils are expansive exhibiting poor consistency properties. The addition of the crushed waste ceramics in the treatment exercise showed that the test soils decreased consistently in their plasticity value. The test soils improved from highly plastic soils to very low plastic soils with highly stiff consistency with further and incremental addition of the CWC. The behavior had resulted from various reasons; the release of cations and the release of carbons by the highly aluminosilicates of CWC at the adsorbed complex zone of the mixed treated soils. These released materials in different states ionization were responsible for the hydration reaction at the initial phase of the treatment protocol. This led to the dissociation of ions under the laboratory moisture content. Subsequently, carbonation and calcination reaction took place at the reaction interface of the reactive minerals from soils and the additives. At the stage, the reactive minerals form floccs with the treated soils giving rise to densified and strengthened blend of treated material. This observed and recorded improvement was due to the hydration of the blend of the highly pozzolanic admixture and the treated soils giving rise to a reduced plasticity index. This equally brought about the formation of the stiff consistency of the treated matrix. The liquid and plastic limits equally reduced at the addition of the CWC to the treated soils. This showed that the moisture content was dependent on the physicochemical properties of the added admixture. This behavior agrees with Onyelowe and Bui Van [16–18] and Van Bui and Onyelowe [40]. This states that as water is used as pore fluid, the influence of the mechanical factors would remain same with an overall reduction in liquid limits of the treated soils on addition of an additives. The addition or treatment of the test soils with the crushed waste ceramics not only achieved a stiff consistency material, but achieved non-frost-susceptible materials with PI less than 15. This behavior is responsible for the pavement failures resulting from the formation of frosts. With the addition of CWC and reduction of plasticity index below 15, the exercise achieved are more durable treated matrix as subgrade foundation material.

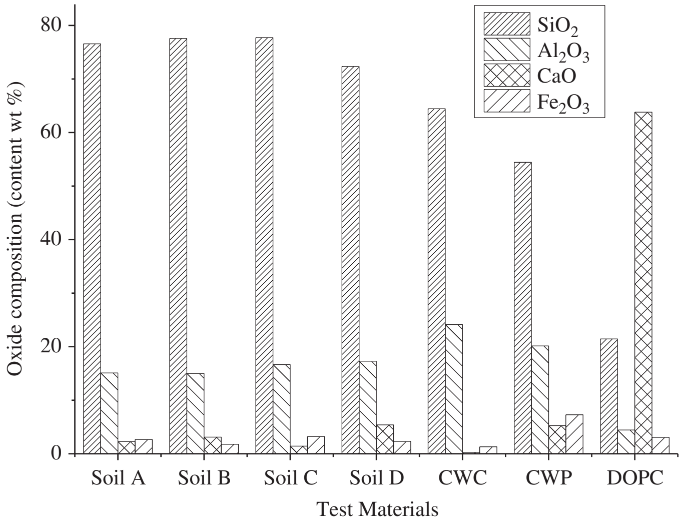

Figure 2. *Primary element oxides found in the studied materials.*

3.2.2 *Compaction characteristics*

The behavior of the maximum dry density of the CWC treated soils A, B, C and D at optimum moisture have been presented in Figure 4. The proportion of treated varied between 0% and 120% of CWC by weight of the treated soils. There was a consistent increase in the maximum dry density with a corresponding decrease in the OMC consistent with the increased proportion of the additive. This behavior was observed to be the same with all the test soils. The specific gravity responded with almost an equal increase at increased proportion of the crushed waste ceramic (CWC). This specific gravity behavior was also consistent with the test soils. The consistent increase in the MDD recorded throughout the test cycles was due to the formation of compounds of calcium and aluminum at the adsorbed complex. This characteristic was as a result of the formation of

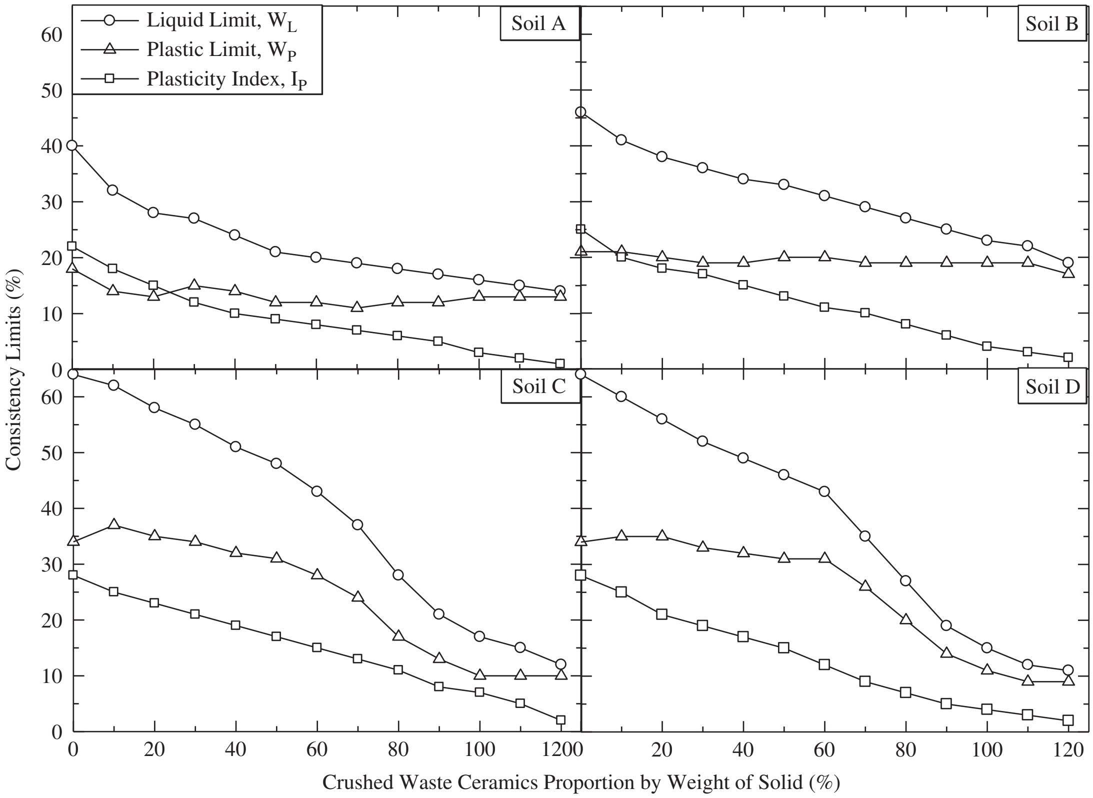

Figure 3. *Effects of CWC on consistency limits of treated soils.*

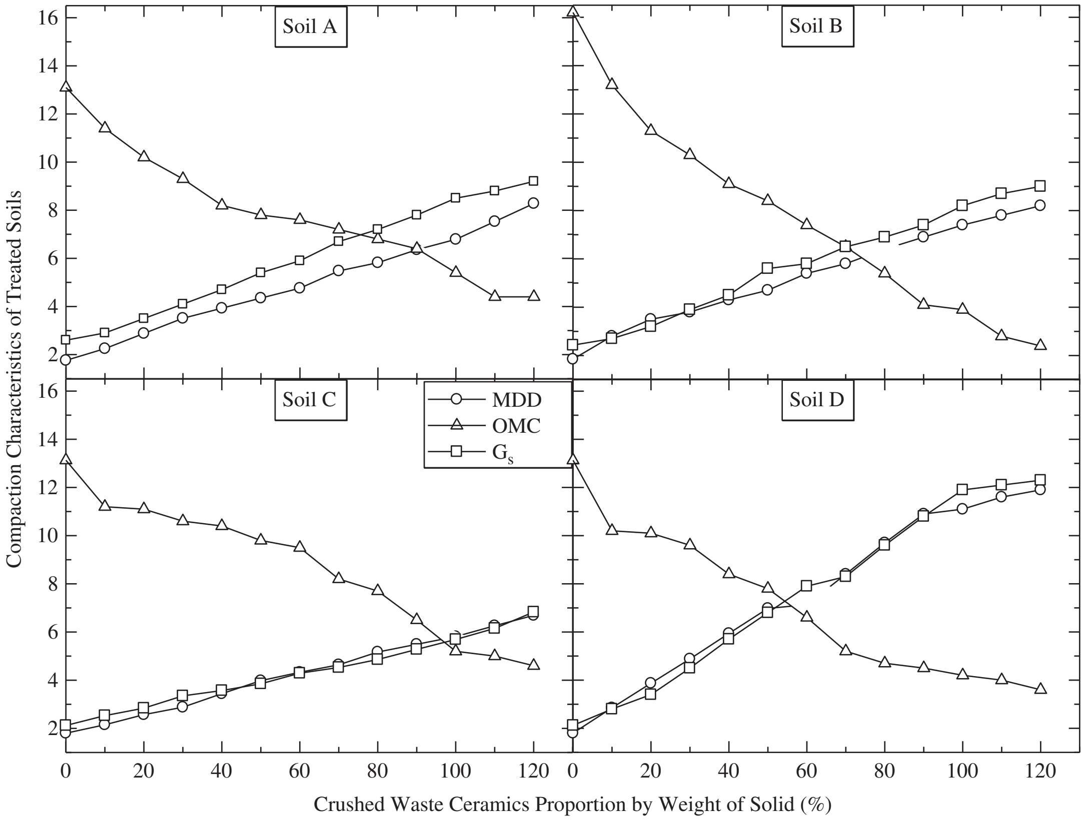

Figure 4. *Effects of CWC on compaction characteristics of treated soils.*

compounds responsible for strength gain through the formation floccs in the treated matrix. This behavior was also due to cation exchange reactions, flocculation, calcination reaction and the filling of the voids within the soil matrix thereby improving the porosity. And in addition, the flocculation and agglomeration of the clay minerals as a result ionization and dipolation, release and exchange of ions [23–34, 45–52]. The reduced moisture utilization was as a result of hydration reaction. Because moisture water was required for the dissociation of constituents with Ca^{2+} and OH^{-} ions to release more Ca^{2+} for the cation exchange reaction [42].

3.2.3 *Stiffness behavior*

3.2.3.1 *California bearing ratio* The California bearing ratio behavior of the CWC treated soils A, B, C and D results is presented in Figure 5. There was a steady strength improvement on the CBR of the treated soils with increase in CWC proportions with a maximum of 48%, 48%, 49% and 45% recorded on test soils A, B, C and D, respectively, at 120% addition of CWC by weight. These values which were greater than 20%, satisfy the materials requirement for utilization as stabilized subgrade material on Nigeria roads (Nigerian General Specification, 1997). The consistent increase in the CBR with the addition of CWC could be due to the presence of sufficient release of calcium required for the formation of hydrated Calcium Silicates (CS) and Calcium Aluminate (CA). These are the major compounds responsible for strengthening [23–34, 45–53]. The soil + CWC mix met the basic California bearing ratio value of 20–30% specified by Onyelowe and Okafor [65] for pavement materials suitable to be utilized as base course materials determined at Maximum Dry Density and Optimum Moisture Content (Figure 5).

3.2.3.2 *Deviatoric stress and resilient modulus (M_R) of the treated cemented soils* The results of the resilient modulus of the treated soils used to characterize the treated matrix as a subgrade materials is presented in Figures 6 and 7. The applied deviator stress and the recoverable strain of the modified triaxial test on the treated specimens were used. The four test soils behaved in almost the same pattern with similar reactions with increased crushed waste ceramics (CWC). The deviatoric stress consistently increased with increase in the proportion of the admixture for test soils A, B, C and D. It is important to note at this point that the additive CWC is a highly aluminosilicate compound with a crystal texture prior to its utilization in the stabilization procedure. These compounds are responsible for pozzolanic reaction, and strengthening by forming silicates of

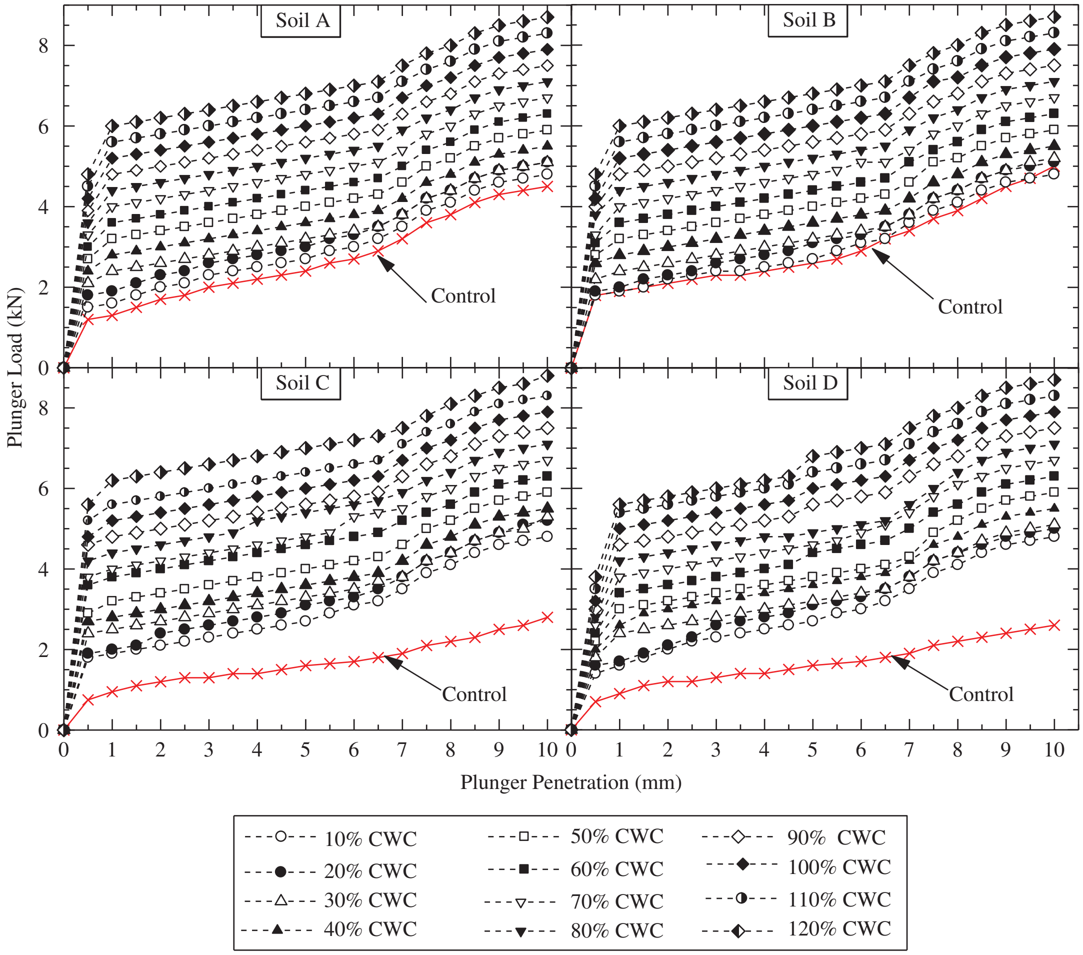

Figure 5. *Effects of CWC on California bearing ratio behavior of treated soils.*

calcium hydrates and aluminates. Test soil A, B and C had an improvement index of about 21%, while test soil D had an improvement index of 25%. The higher improvement index recorded with test soil D is in line with its natural soil high resilient modulus of 0.72E+05 which was improved upon. The hydration reaction between compounds of strengthening from the additive and the dissociated soil ions in contact with moisture had caused the improvement on both deviatoric stress and resilient modulus of the test treated soils. These results were recorded under cyclic loading on specimens subjected to testing sequences. The physical conditions that affect the resilient modulus (moisture and unit weight) were influenced by the introduction of the highly aluminosilicate CWC hence improving the strength behavior of the treated soils [23–34, 45–53].

3.2.3.3 *Lateral deformation and resistance value (*R*-Value) of the CWC treated test soils* The results of the stabilometer test adapted with the modified triaxial compression test set up for the CWC treated test soils are presented in Figures 8–11. This was conducted on the treated soils to determine the treated soils ability to resist lateral deformation when subjected to both horizontal and vertical pressure loading of the stabilometer under laboratory conditions. The results showed a consistent reduction in the deformation over a consistent improvement on the resistance value of the treated soils subjected to the dual loading arrangement. The deformation on the treated soils increased with increased pressures but reduced with increased addition of the CWC. The *R*-value also improvement consistently with increased proportions of the additive but reduced under increased pressure (vertical and horizontal) of the stabilometer. The index of reduction of the deformation with increased CWC was recorded at 23% for test soil A, 21% for test soil B, 24% for test soil C and 28% for test soil D. similarly, the improvement index on the *r*-value of the treated soils were recorded as 34%. 32%, 36% and 38%, respectively, with increased proportions of CWC by weight. This is behavior was due to the ability of the pozzolanic compounds and the aluminosilicate strength of the additive

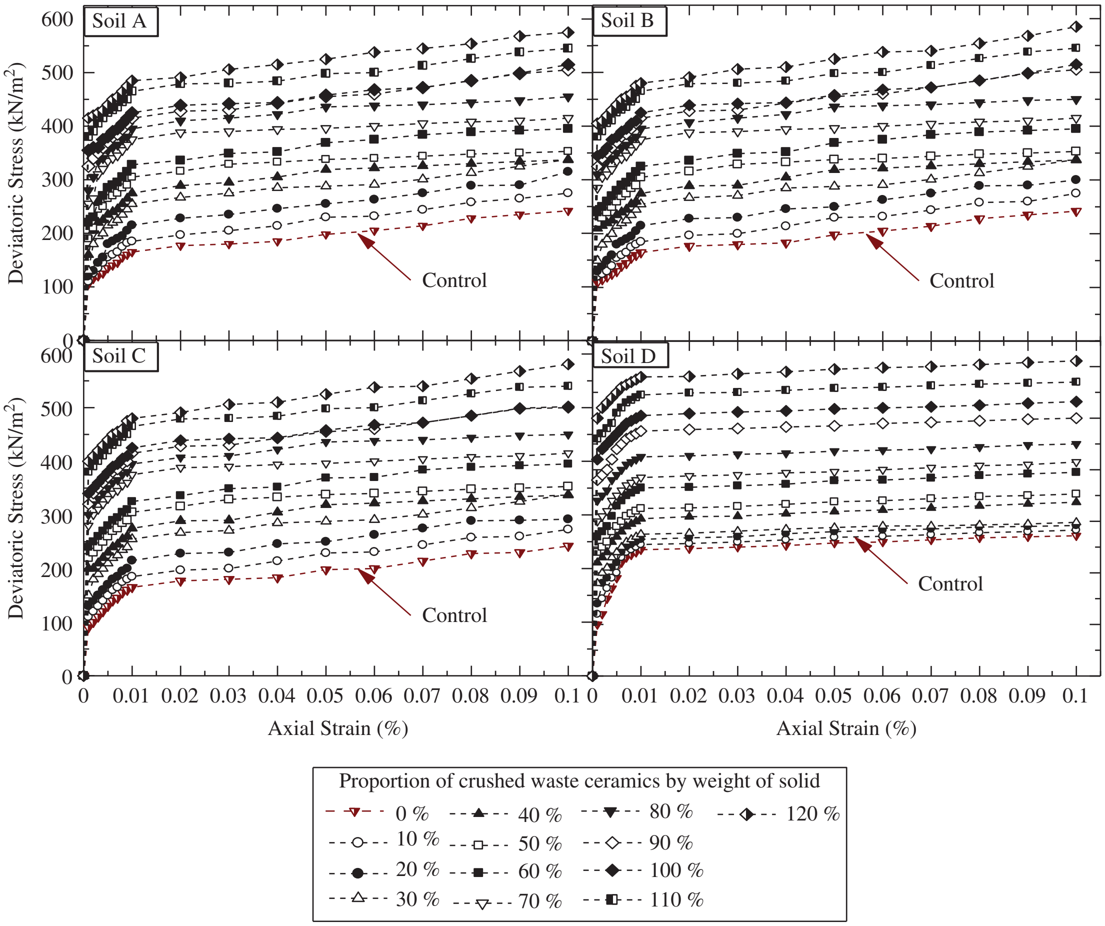

Figure 6. *Effects of CWC on deviatoric stress of the treated cemented soils.*

to for floccs and densified matrix compacted at optimum moisture content [23–34, 45–53]. The crystalline particles of the CWC filled the pore spaces of the treated soils thereby improving the porosity of the soils matrixes hence achieving high resistance value test soil materials suitable as subgrade and sub-base pavement materials of high stiffness. The measure of the failure of pavements is based on both shear and lateral failure. While CBR and resilient modulus gives a clue to monitoring the failure of pavements by shear, the r-value gives an expert guideline of the resistance of the pavement material to displacement.

3.3 Effects of crushed waste plastics on behavior of treated soils

3.3.1 *Consistency limits behavior*

Consistency behavior of 2.5% DOPC and varying proportions of CWP treated test soils was presented in Figure 12. Preliminary results had shown that the test soils were classified as highly plastic soils with high clay content responsible for the volume changes in moisture. This property in effect shows that the soils are expansive exhibiting poor consistency properties. The addition of the crushed waste plastics (CWP) in the treatment protocol showed that the test soils decreased consistently with the plasticity value. The test soils improved from highly plastic soils to very low plastic soils with highly stiff consistency with further and incremental addition of the CWP. The behavior had resulted due to; the release of cations exchange by the highly aluminosilicates of CWP at the double diffused layer (DDL) zone of the blended treated soils. These released materials in different states of ionization were responsible for the hydration reaction at the initial phase of the treatment protocol. This led to the dissociation of ions under the laboratory moisture content. Subsequently, carbonation and calcination reaction took place at the reaction interface of the reactive minerals from soils and the additives. At this stage, the reactive minerals form floccs with the treated soils giving rise to densified and strengthened blend of treated material. This observed and recorded improvement was due to the hydration of the blend of the highly pozzolanic admixture and the treated soils giving rise to a reduced plasticity index. This equally brought about the formation of the stiff consistency of the treated matrix. The liquid and plastic limits equally reduced at the addition of the

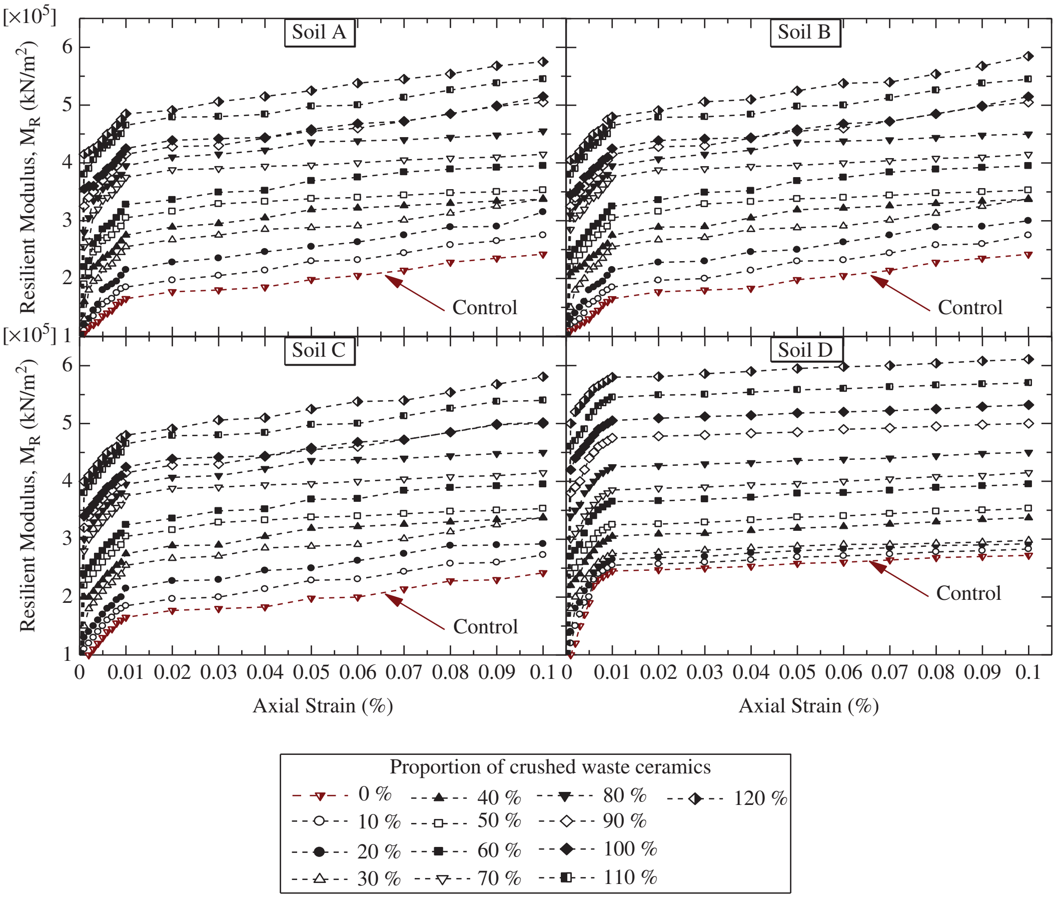

Figure 7. *Effects of CWC on resilient modulus, M_R, of the treated cemented soils.*

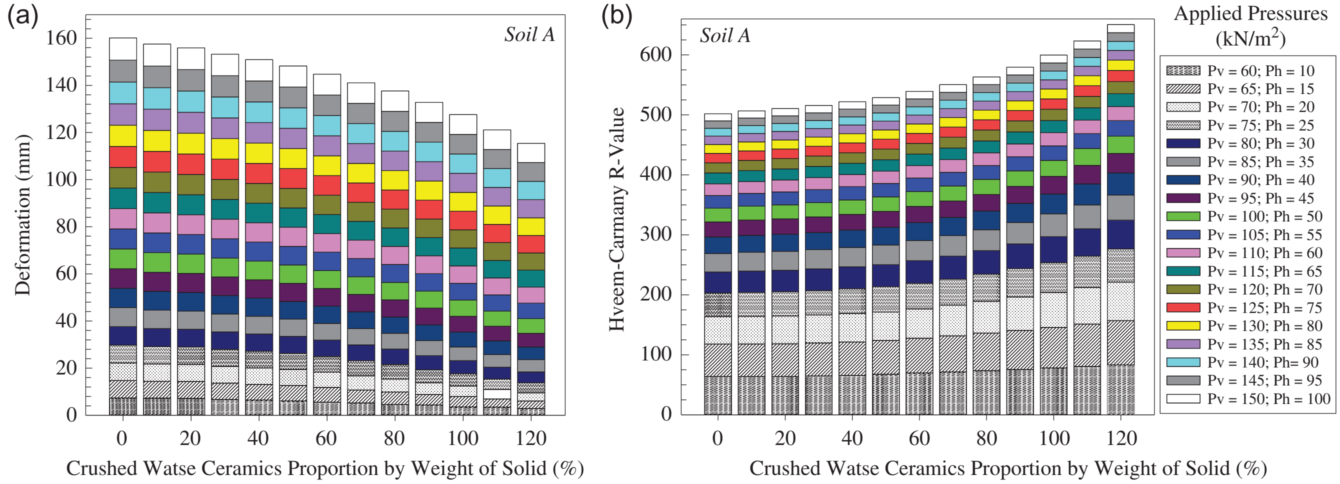

Figure 8. *Effect of CWC on deformation (**a**) and* R*-value behavior of treated soil A (**b**).*

CWP to the treated soils. This showed that the moisture content was dependent on the physicochemical and elastic properties of the added admixture [23–34, 45–53]. This states that as water is used as pore fluid, the influence of the mechanical factors would remain same with an overall reduction in liquid limits of the treated soils on addition of an additives. The addition

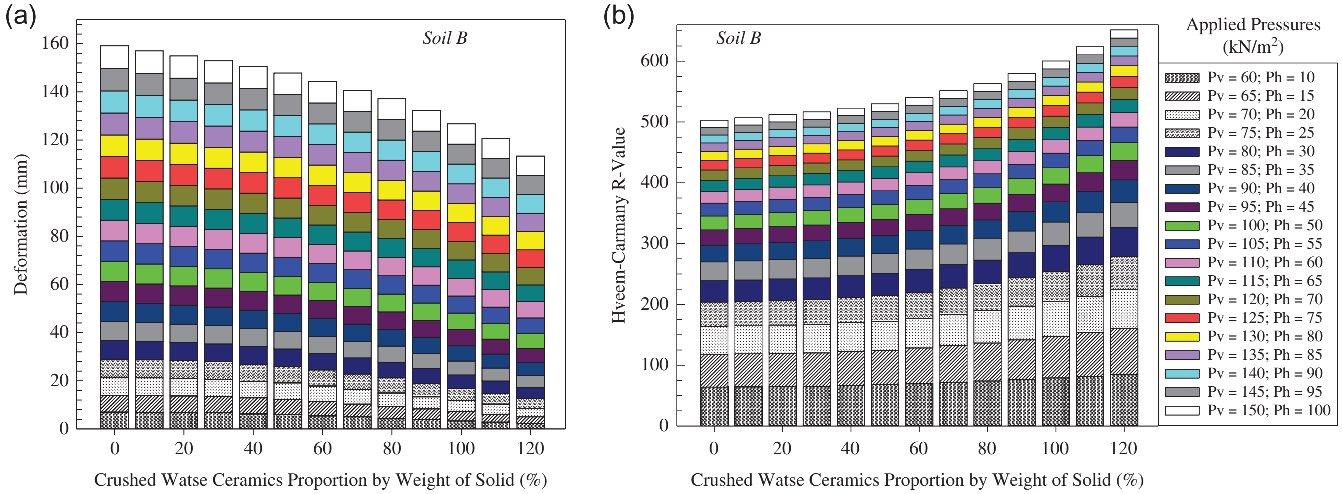

Figure 9. *Effect of CWC on deformation and* R*-value behavior of treated soil B.*

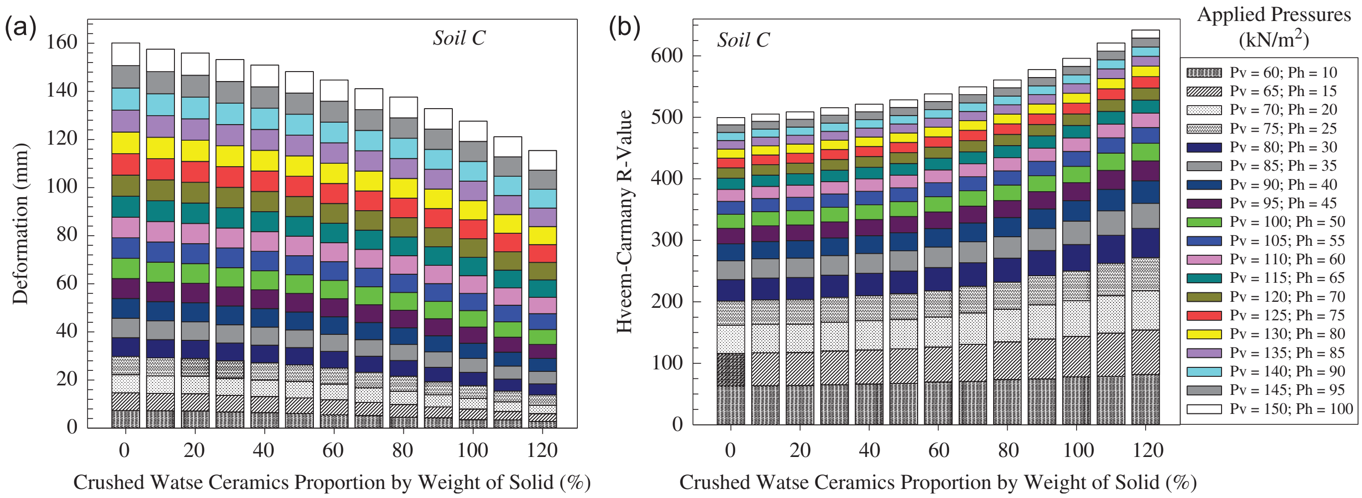

Figure 10. *Effect of CWC on deformation and* R*-value behavior of treated soil C.*

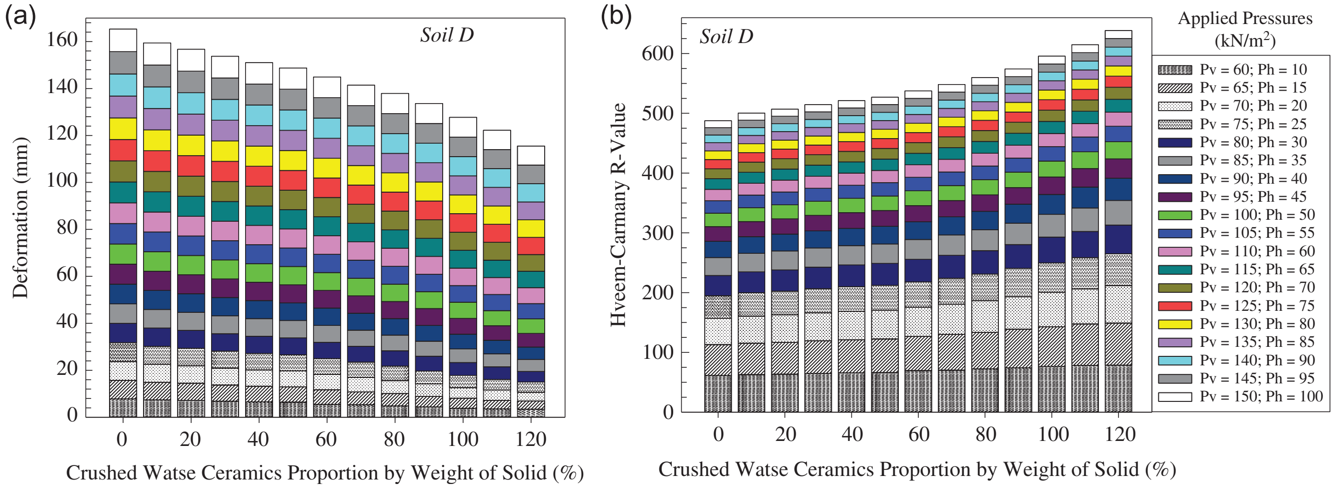

Figure 11. *Effect of CWC on deformation (**a**) and (**b**)* R*-value behavior of treated soil D.*

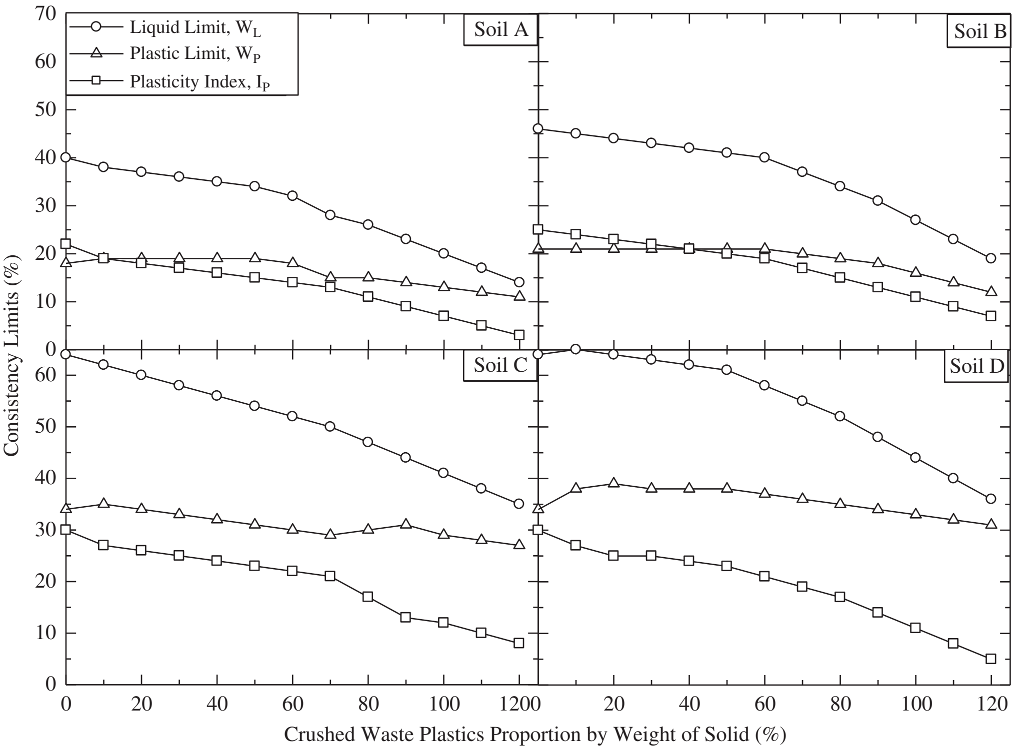

Figure 12. *Effect of CWP on the consistency limits of treated soils.*

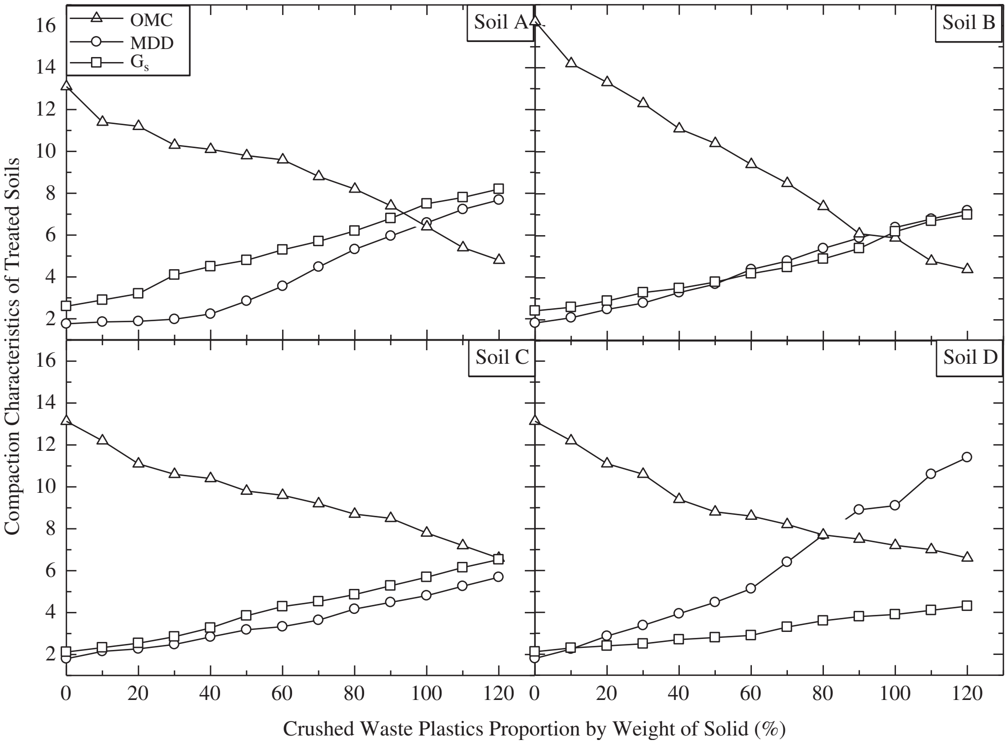

Figure 13. *Effects of CWP on compaction characteristics of treated soils.*

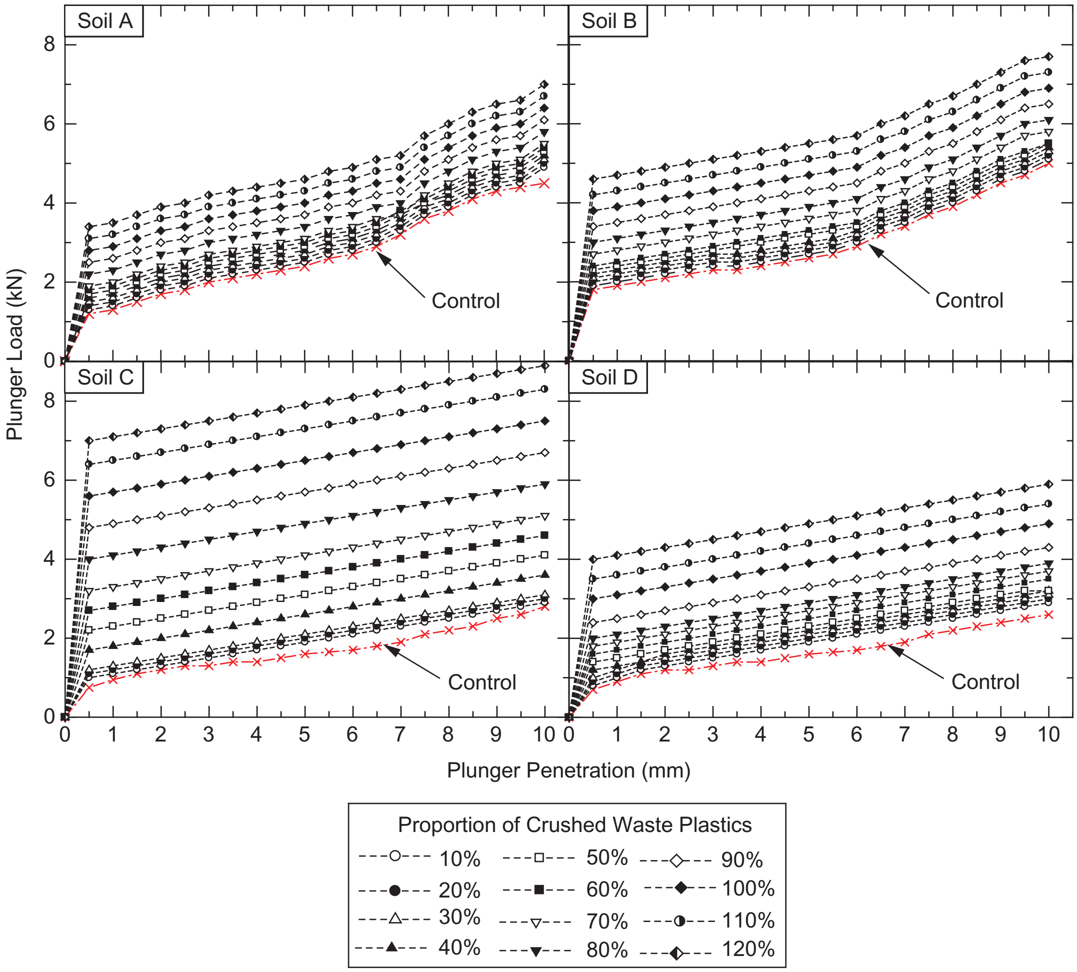

Figure 14. *Effects of CWP on California bearing ratio of treated soils.*

or treatment of the test soils with the crushed waste plastics not only achieved a stiff consistency material, but achieved non-frost-susceptible materials with PI less than 15. This behavior is responsible for the pavement failures resulting from the formation of frosts. With the addition of CWP and reduction of plasticity index below 15, the exercise achieved a more durable treated matrix as subgrade foundation material.

3.3.2 *Compaction characteristics*

The behavior of the maximum dry density of the CWP treated soils A, B, C and D at optimum moisture has been presented in Figure 13. The proportion of additive varied between 0% and 120% of CWP by weight of the treated matrix. There was a consistent increase in the maximum dry density with a corresponding decrease in the OMC consistent with the increased proportion of the additive. This behavior was observed to be the same with all the test soils. The specific gravity responded with almost an equal increase at increased proportion of the crushed waste ceramic (CWP). This specific gravity behavior was also consistent with the test soils. The consistent increase in the MDD recorded throughout the test cycles was due to the formation of compounds of calcium and aluminum at the adsorbed complex. This characteristic was as a result of the formation of compounds responsible for strength gain through the formation floccs in the treated matrix. This behavior was also due to cation exchange reactions, flocculation, calcination reaction and the filling of the voids within the soil matrix thereby improving the porosity. And in addition, the flocculation and agglomeration of the clay minerals as a result ionization and dipolation, release and exchange of ions [23–34, 45–53]. The reduced moisture utilization was as a result of hydration reaction. Because moisture water was required for the dissociation of constituents with Ca^{2+} and OH^{-} ions to release more Ca^{2+} for the cation exchange reaction [42].

3.3.3 *Stiffness behavior of CWP treated soils*

3.3.3.1 *California bearing ratio* The observations of the effect of the crushed waste plastics on the California bearing ratio (CBR) of the treated soils A, B, C and D are presented in Figure 14. CBR is the measure of the ability

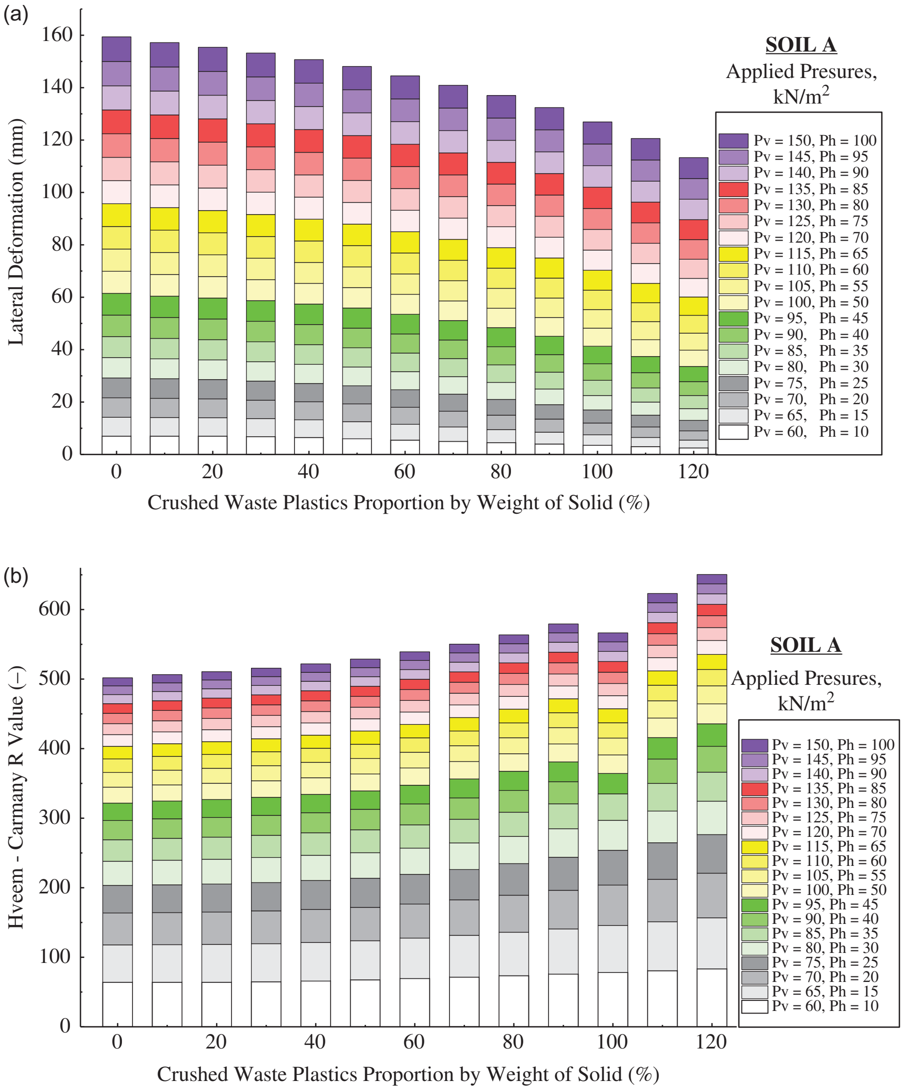

Figure 15. *Effect of CWP on lateral deformation (**a**), and (**b**) R-value behavior of treated soil A.*

of materials to resistance failure by shearing. It is an axial failure resistance measurement. The test soils had initial CBR values of 12, 13, 8 and 7% respectively achieved at maximum dry density and optimum moisture content. The soils were treated with CWP at the proportions of 10 to 120% in increments of 10% by weight of the dry solid. This admixture possessed a high content of aluminosilicates and exhibited pozzolanic properties with elastic properties. The blends between the test soils and CWP were compacted and tested for axial failure resistance. Test soils A, B and D showed similar behavior with the addition of CWP while soil C behaved somewhat differently. This is due to the fact that test soil C recorded the highest liquid limit, plastic limit and lowest shrinkage limit at the natural but disturbed state. The CBR of the treated test soils consistently improved with increased CWP content and recorded CBR values of 30, 38, 56 and 33% respectively at 120% by weight proportion of CWP. This shows a further potential of improvement on addition of CWP to the treated soil matrix. This behavior was as a result of the pozzolanic reaction between the aluminosilicate compounds of the additive and the test soils where the mixed matrix formed sequestrum and floccs with the additive. This reaction improved the calcination reaction and enhanced strength gain and densification. Cation exchange reaction within the double diffused layer of the mixed matrix of treated soils and additive also contributed to the strength improvement and resistance to shear failure of the treated soils [23–34, 45–53].

3.3.3.2 *Lateral deformation and resistance value (*R*-value) of the CWP treated test soils* The lateral deformation and resistance value laboratory exercise of the crushed waste plastics treated test soils are presented in Figures 15–18.

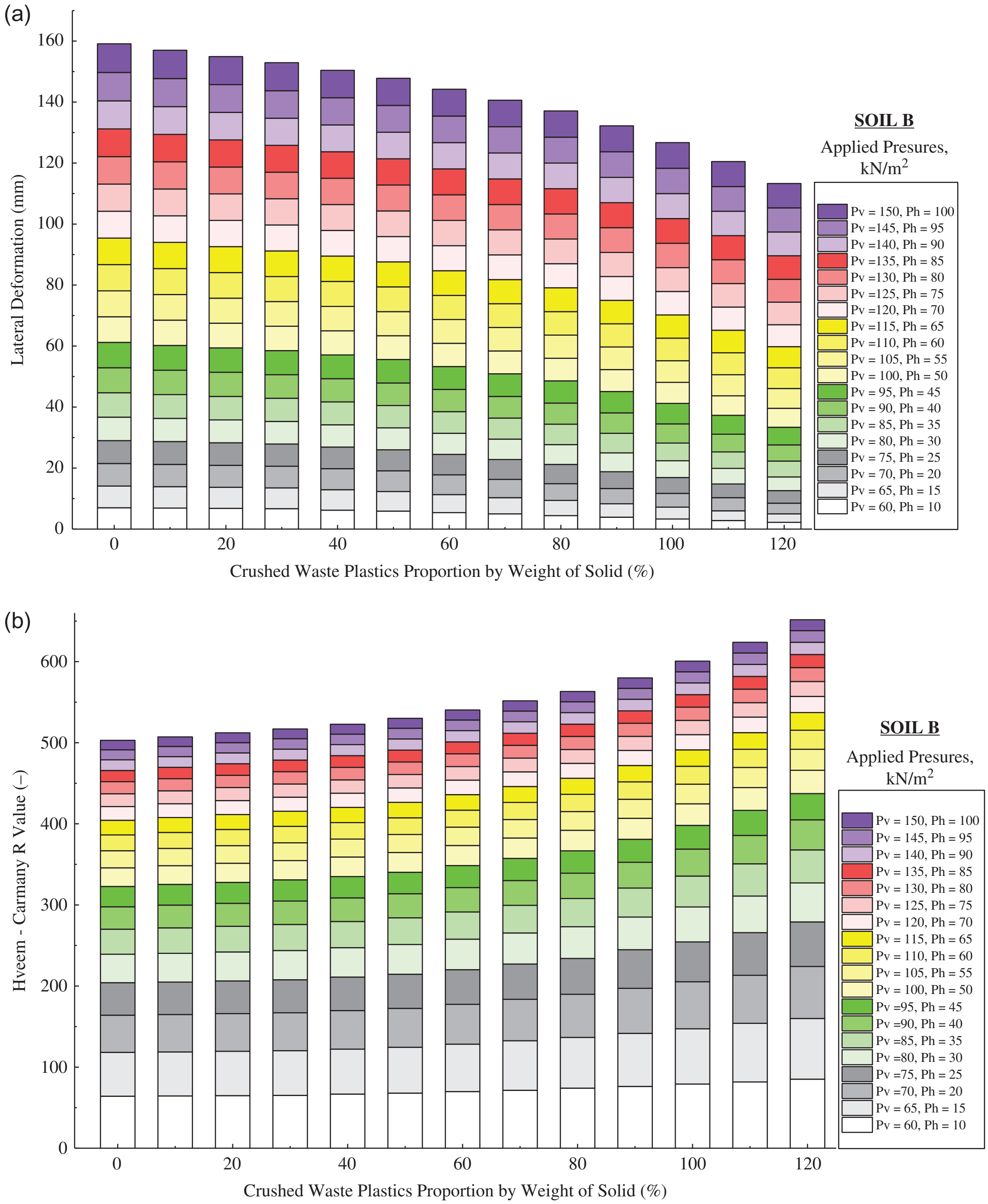

Figure 16. *Effect of CWP on lateral deformation (a), and (b)* R-value *behavior of treated soil B.*

The treated specimens were subjected to a modified triaxial compression test consisting of a combination of vertical and horizontal pressures. The lateral deformation consistently reduced with increased proportions of CWP which was added in the proportion of 10%, 20%, 30%, to 120%. The recorded increased resistance to deform was due to the formation of silicates and aluminates of calcium under hydrated laboratory conditions. This also led to the formation of densified matrixes of treated specimens that defied the effect of the pressures that they were subjected to. This goes to show that the treated soils achieved the ability to resist lateral cyclic loads like traffic loads when subjected to the highway traffic conditions with the increased addition of crushed waste plastic

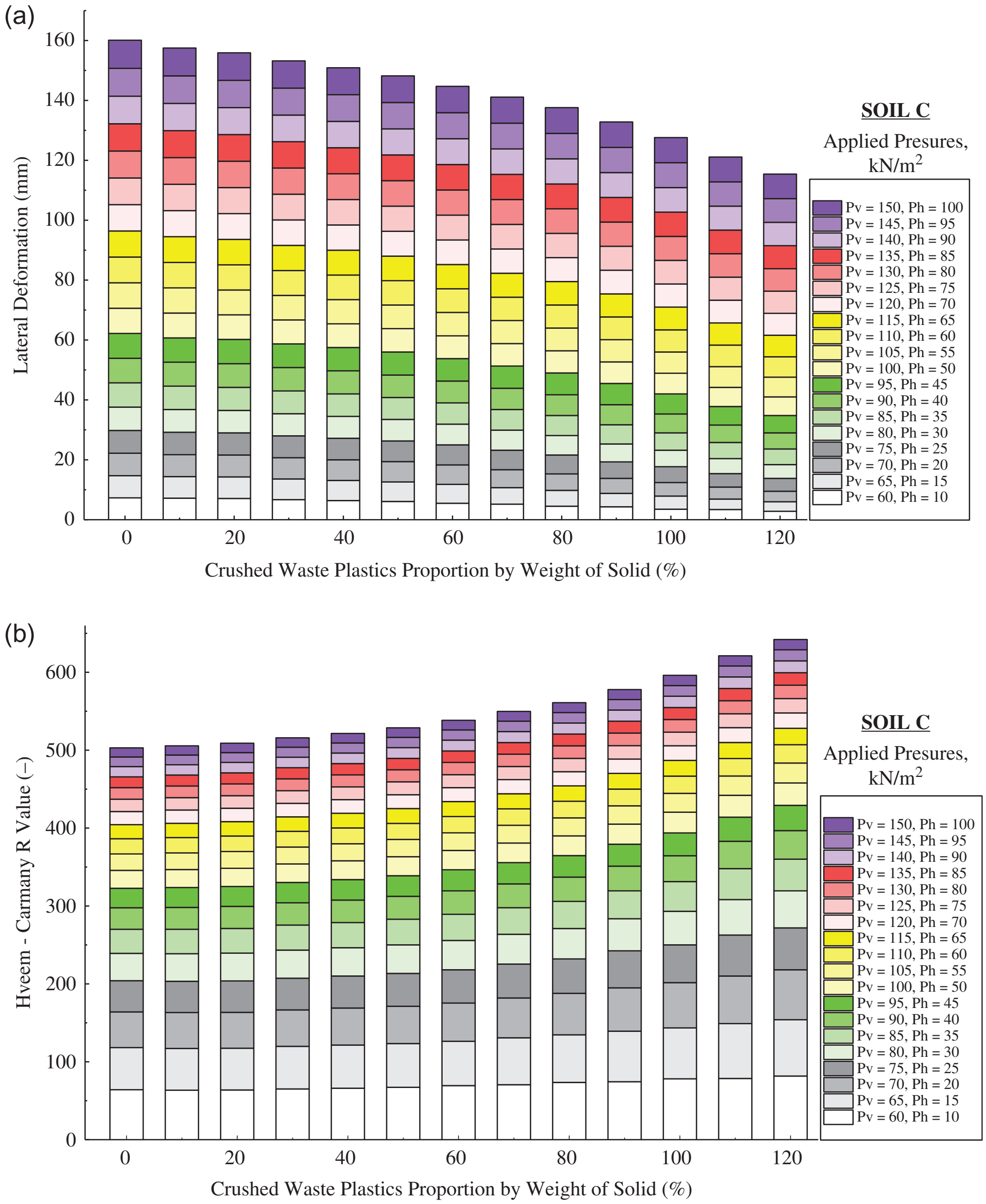

Figure 17. *Effect of CWP on lateral deformation (**a**), and (**b**)* R*-value behavior of treated soil C.*

materials. The sequestrum and floccs that were formed at the adsorbed complex of the treated materials improved the laboratory performance of the soils treated with CWP. Cation exchange reaction also caused a released of the compounds of silicates and aluminates responsible for strengthening in stabilized treated soils. This behavior also caused the consistent reduced lateral deformation on addition of the admixtures by weight. Similarly, the resistance value of the four test soils were improved consistently with the addition of the CWP under the applied pressures of the modified triaxial compression condition. The hydration reaction at optimum moisture and maximum dry density of the treated matrixes was responsible for the buildup of the resistance value of the treated soils. Also, polymerization reaction of the plastic compounds with the test soils when mixed with the optimum moisture condition help the soils achieve a consistent improvement in the resistance value (r-value). Resistance value is dependent on the lateral deformation. The foregoing implies that resistance value is inversely proportional to the lateral deformation, which further implies that when lateral deformation reduces as a result of the addition of geomaterials responsible for strength gain, the resistance value improves. This is the case in

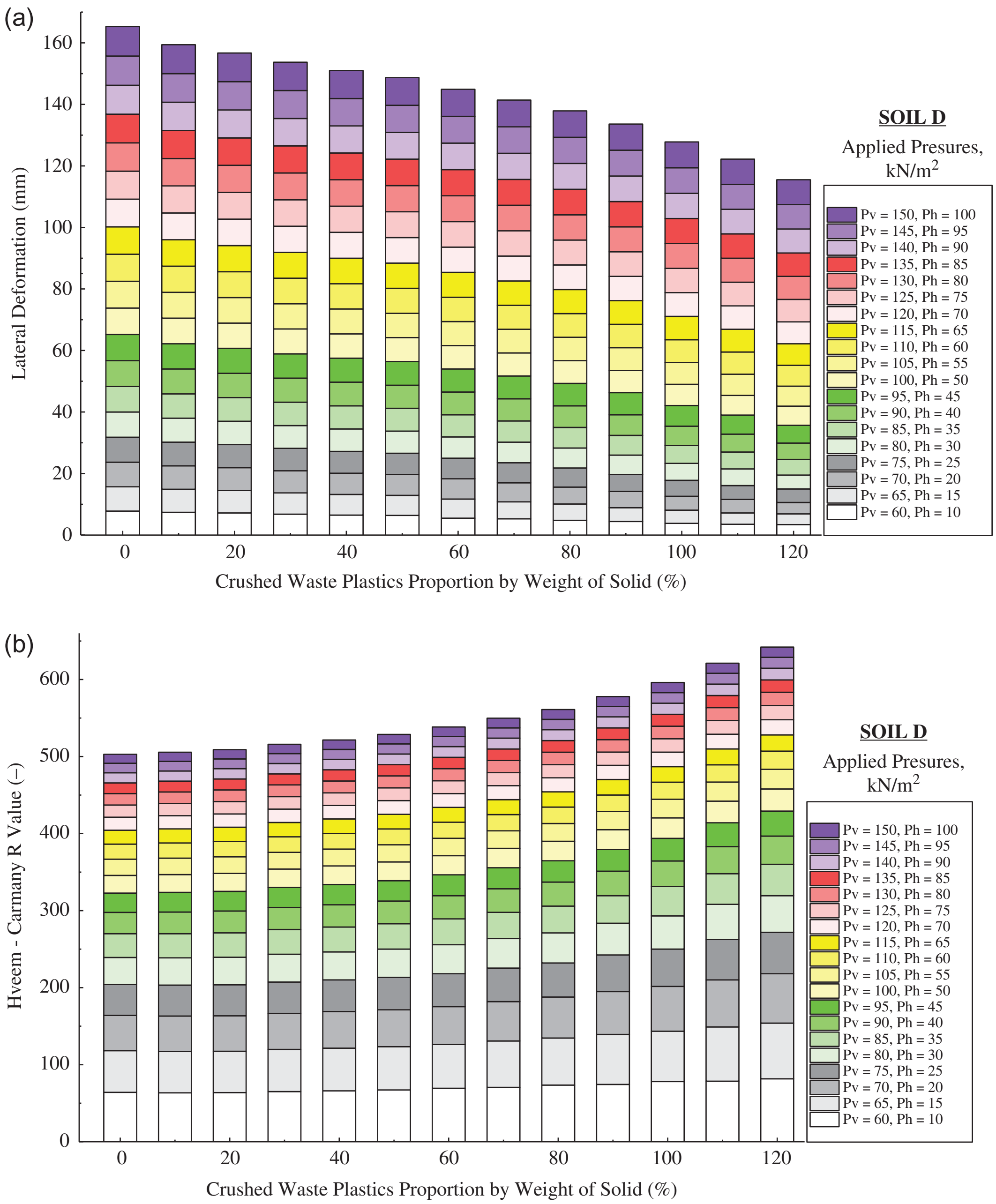

Figure 18. *Effect of CWP on lateral deformation (a), and (b)* R*-value behavior of treated soil D.*

the present work. It is novel to achieve an improved *r*-value with a geomaterial from solid waste [23–34, 45–53, 61, 66].

4 CONCLUDING REMARKS

The following remarks best conclude the present research work;

(i) the increased proportions of crushed waste plastics and crushed waste ceramics consistently improved the California bearing ratio characteristics of the treated soils A, B, C and D.

(ii) The increased proportions of the crushed waste plastics and crushed waste ceramics improved the resilient modulus of the treated test soils.

(iii) The varied proportions of the crushed waste plastics and crushed waste ceramics also improved the resistance value (R-value) of the treated test soils and thereby reduced the lateral deformation.

(iv) Finally, it is novel to have achieve improved California bearing ratio characteristics, resilient modulus, resistance value and lateral deformation properties of the test soils with a solid waste based geomaterial. With the achieved properties, the test soils form a good foundation material for pavements when treated with the proportions used in the laboratory exercises. It is also promising that beyond the proportion utilized in the laboratory, the CWC and CWP treated soils will resist both axial and lateral deformation or failure when compacted to the maximum dry density and optimum moisture.

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CONFLICT OF INTEREST

There are no conflict of interests recorded in this research.

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