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Adsorbed Complex and Laboratory Geotechnics of Quarry Dust (QD) Stabilized Lateritic Soils

Onyelowe Kennedy¹, Bui Van Duc²

¹Department of Civil Engineering, Michael Okpara University of Technology, Umudike, Umuahia, Nigeria. Email: konyelowe@mouau.edu.ng, konyelowe@gmail.com

²Faculty of Civil Engineering, Hanoi University of Mining and Geology, Hanoi, Vietnam. Email: buivanduc@humg.edu.vn

Highlights

- Test soil was studied and Characterized
- Quarry dust was also characterized
- Quarry dust was blended with the test soil in a stabilization protocol
- The effects of the addition of the quarry dust on the adsorbed complex of the treated soil diffused layer was studied

Abstract

The effect of ordinary Portland cement, OPC+ Quarry Dust, QD on the adsorbed moisture, diffused double layer (DDL), dielectric constant, density and repulsion potential (RP) of treated lateritic soil was investigated through laboratory tests. The preliminary tests showed that the natural soil was an A-2-7 soil, according to the AASHTO classification system, highly plastic soil and high swelling potentials. The soil was treated with a fixed 5% OPC and varying proportions of QD at 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50% by weight of the dry soil. The stabilization results showed that the compaction properties improved consistently, with the addition of the QD. Also, the addition of the QD reduced the adsorbed moisture and consequently reduced the double diffused layer and the repulsion potential, which constitute the properties investigated within the adsorbed complex in the stabilization operation. These observations brought about the cation exchange reaction between the metallic ions that were attracted to the adsorption complex, resulting to densification, flocculation from the natural state of dispersion of particles and strength gain in the stabilization procedure. Results also showed that the repulsion potential increased in magnitude with the distance between the reactive particles and the clay surface and reduced with increased proportions of QD. The dielectric constant also reduced considerably with adsorbed moisture, which indicated that the dielectric was affected by the moisture and the ions released within the adsorbed complex.

Keywords: Adsorbed Water; Lateritic Soils; Geotechnical Engineering; Soil Stabilization; Soil-Nanostructured Ash Interaction.

1. Introduction

Adsorbed moisture is the moisture located within the influence zone of the contact between water and clay particles whose properties are very viscous and different from those of free or normal water at the same temperature (Das, 2010; 2011; Das and Sobhan, 2012). The behaviour of soil matrix depends upon the behaviour of the discrete elements composing the matrix and the structural pattern of the particles organization (Das, 2008; 2010; Smith and Smith, 1998). In all these states, moisture plays a very important role as it is applied in soil stabilization at different moisture contents and dry densities. The reaction of the soil matrix is profoundly influenced by the inter-particle-water relationships, the ability of the soil elements to adsorb exchangeable cations and the amount of moisture present and free to react, which also depends on the orientation of the net ions within the clay matrix and the dipolar water (Das, 2011). The clay particles carry negative charge on their surface and this is the result of isomorphous substitution and of a discontinuity of the structure at its edges (Das, 2003; 2008). As it's mentioned above, cation exchange is a process by which stronger cations in the metallic elemental series displace weaker ions. Electrolytes dissociate when dissolved in moisture into positively charged cations and negatively charged anions like water which dissociates into hydrogen cation H^+ and hydroxyl anion OH^- . These positively charged ions migrate to the surface dominated by the negatively charged clay particles and form the adsorbed layer. From the metallic order of the ions, these H^+ ions can be replaced by the other cations such as Ca^{++} , Al^{+++} , Na^+ , K^+ , or Mg^{++} (Das, 2003). When these ions migrate into the adsorbed layers, they constitute the "adsorption complex". This process of replacement of one kind by those of stronger kind within the adsorption complex is known as "Base Exchange", which is meant the capacity of colloidal particles to change the cations adsorbed on their surface. This takes place by a constant percolation of water containing dissolved sodium salts. And the quantity of the exchangeable cations in a soil matrix is called "exchange capacity". The above illustrations are the mechanics of the interaction that take place in any soil stabilization operation. In Geotechnical engineering works, weak soils call for a need to carry out stabilization to chemically or mechanically change the properties of such soils to make them usable and serviceable to the Geotechnical engineer. And soils used in Geotechnical engineering services are made primarily of clay. Clay minerals as are contained in lateritic soils are complex aluminium silicates compounds of one of two basic units which are tetrahedral units of four oxygen atoms surrounding a silicon atom forming silica sheets and the octahedral units of six hydroxyl compounds surrounding an aluminium atom forming gibbsite sheets or surrounding a magnesium atom forming brucite sheets (Das, 2003; 2008; 2010; 2011). These are the major building block of clay minerals. When soils are subjected to stabilization by a combined effect of chemical, mechanical and admixture procedures and processes, ions are released within the interface between the clay particles and the additives. The dominant negative ions from clay are balanced by exchangeable cations like Ca^{++} , Mg^{++} , Na^+ and K^+ from the additives surrounding the particles being held by electrostatic attraction and the van der Waal's force (Das, 2003; 2008; Nnochiri and Ogundibe, 2016). The release of the ions on the other hand depends also on the oxide composition of the additives. At the point that moisture is added to the soil matrix being stabilized, these cations and a small number of anions float around the clay particles within the diffused double layer (DDL) (Das and Sobhan, 2012). Research has shown that cation concentration decreases with the distance from

the surface of the particles while the anion concentration increases but slowly. For flocculation, densification and strength gain to be complete in a stabilization operation, there must be a comprehensive cation exchange which is to say that the distance between the particles has to be reduced to improve the cation concentration. If we assume that the ions in the double layer can be treated as point charges and that the surface of the stabilized clay elements is large compared to the thickness of the double layer, poisson's equation states,

$$\frac{d^2\Phi}{dx^2} = -\frac{4\pi\rho}{\lambda} \quad (1)$$

Where Φ = repulsion potential, ρ = density of medium, λ = dielectric constant and the x = distance between charged particles and clay surface

The repulsion potential is the tendency for the distance between the particles which we consider as charged points to increase thereby reducing the potentials for the stabilized matrix to form floccs and eventually gain strength and density. Hence, the primary aim of this research work was to study the influence of ordinary Portland cement+quarry dust treatment on the repulsion potential in a stabilized soil matrix. And the specific objectives of this research were; (i) to review relevant literature, (ii) to study through laboratory results, the effect of cement + varying proportions of quarry dust (QD); between 0 and 50% by weight on dielectric constant, matrix density, adsorbed moisture, repulsion potentials, and (iii) to study the influence of QD lateritic soil treatment on the distance between particles and clay surface and the repulsion potential relationship and (iv) to report the findings of this research work and eventually publish same for cause of research. Many practical procedures and methods have been applied over the years by researchers and geotechnical constructors to enhance the properties of weak lateritic soils. These include the use cement and other cementitious additives like fly ash, lime, blast furnace slag, etc. (Dharamveer et al. 2017; Masaki and Eiji, 2006; Ojuri et al. 2017; Okafor and Ewa, 2012; Okonkwo et al. 2016). A lot more have applied ash materials like bagasse ash, derived lateritic gravels, palm bunch ash, nanostructured clay, waste paper ash, etc. to achieve strength gain and stabilization of weak engineering soil (Onana et al. 2017; Osinubi et al. 2009; Okonkwo et al. 2016; Etim et al. 2017; Abdorelza et al. 2017; Anand, 2016; Onyelowe, 2017a, b, c; Onyelowe et al. 2017; Onyelowe and Okafor, 2015; Onyelowe and Ubachukwu, 2015; Onyelowe and Agunwamba, 2012). In recent times, experts have applied different classes of Geosynthetics and nanostructured additives to achieve improved soil properties (Xiao et al. 2005 Ahmad et al. 2013; Ali et al. 2011; Anitha and Haresh, 2014; Cheng et al. 2013; Cuelho and Perkins, 2017; Hedge and Sitharam, 2017; Laila et al. 2010; Mousavi, 2017). There have also been mechanical procedures employed to alter the consistency and compaction properties of the stabilized soils for construction purposes (Bolarinwa et al. 2017; Abdullahi et al. 2017; Okafor and Egbe, 2017; Samuel et al. 2017; Wong, 2017; Yawen et al. 2014; Xuecheng et al. 2016) The results achieved from these operations are applied in transportation infrastructures, mechanically stabilized earth (MSE) structures, dams, etc. (Gomes et al. 2016; Gidigas and Dogbey, 1980; Garg, 2005; Buddhima, 2016; Bent, 1996; Anamika et al. 2012; Fwa, 2006; Phillip et al. 2016).

2. Technical Approach and Materials Preparation

The technical approach was carried out in three phases; preparation of materials (lateritic soil and quarry dust), laboratory exercises and expansion of the parametric equation and the comparative study of the effect of the treatment on the physical parameters of the repulsion potential equation.

2.1 Materials

Quarry Dust presented in Figure 1 was collected from the Quarry Factory in Amasiri, Afikpo, Nigeria. This was applied in the proportions of 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50% by weight to treat the lateritic soil. Ordinary Portland cement used as at a fixed percentage of 5% was Dangote cement bought from the Umuahia Timber Market that satisfies the cement materials condition in accordance with ASTM C150 (2013). Lateritic soil sample used for this study was collected from the borrow pit located at Olokoro, on latitude of 05°28'36.700" North and longitude 07°32'23.170" East from a depth of 1.5 meters, a distance of 5km off Ubakala road from the Ishi Court junction, Umuahia, Abia state capital, Nigeria. The sample collected was in solid state and reddish brown in color. The soil was air dried in trays for six days, after which the soil was tapped with rubber pestle to remove lumps.



Fig. 1. Quarry Dust

2.2 Laboratory Methods

The following preliminary tests were conducted; Sieve Analysis Test was conducted with a vertically arranged sieve sizes mounted on an automatic shaker on both soil and QD, Compaction Test (Standard Proctor Test) was conducted with 2016 ELE Automatic Compactor Machine in accordance with BS 1377-2 and BS 1924 (1980), the California Bearing Ratio Test (CBR) was conducted with a 2015 S211 KIT CBR penetration machine, motorized 50KN ASTM used to load the penetration piston into the soil sample at a constant rate of 1.27 mm/min (1 mm/min to BS Spec.), and to measure the applied loads and piston's penetrations at determined intervals in accordance with BS 1377-2 (1980), Atterberg Limit Test was conducted using a 2013 cassagrande apparatus in accordance with BS 1377-2 (1980), Specific Gravity Test was conducted by pycnometer method in accordance with BS 1377-2 (1980) and Chemical Composition Test was carried out on both the natural soil and the QD, and finally, the capacitance between stabilized and compacted matrixes in the standard proctor mould was determined using the steel electrodes on the various treated soils in accordance to Reuss' experimental set up (Hausmann, 1990) and results were

obtained. The observed capacitances of the stabilized soils were used to determine the dielectric constants at the various treatments as follows (Ling et al. 2016);

$$\lambda = \frac{C \cdot d}{\epsilon_0 A} \quad (2)$$

Where λ = dielectric constant, C = capacitance, d = distance between steel electrodes; which were spaced at 0.1 m from one another, ϵ_0 = permittivity of space = $8.854 \cdot 10^{-12}$ (F/m) (Das, 2003; Ling et al. 2016), and A = surface area of the compaction mould = 0.0081 m^2 (Smith and Smith, 1998)

2.3 Parametric Expansion and Application

Solving Equation 1 with respect to x,

$$d^2 \Phi = -\frac{4\pi\rho}{\lambda} dx^2 \quad (3)$$

Taking double integral of Equation 3 with respect to x,

$$\int \int_0^x d^2 \Phi = \int \int_0^x -\frac{4\pi\rho}{\lambda} dx^2 \quad (4)$$

$$\Phi_{(x)} = \lim_{0 \rightarrow x \rightarrow d} \left(-\frac{2\pi\rho}{\lambda} x^2 \right) \quad (5)$$

Equation 5 implies that the repulsion potential attains its maximum value when $x = d$. There is a magnitude of the repulsion potential at different points within the adsorption complex and beyond the surface of the clay surface. Equation 5 was used to factor out the values of the repulsion potential at these points and the intervals within and around the clay material being stabilized to determine the influence of treatment on the physical parameters of the complex.

3. Results and Discussions

The results of the preliminary laboratory test conducted on the lateritic soil are as presented in Table 1 and it showed that the lateritic soil was an A-2-7 soil according to AASHTO classification system. The consistency test results showed that the soil was highly plastic, high swelling potential and poorly graded. The grading of the soil and the QD are presented in Table 2 and Figure 1.

Table 1

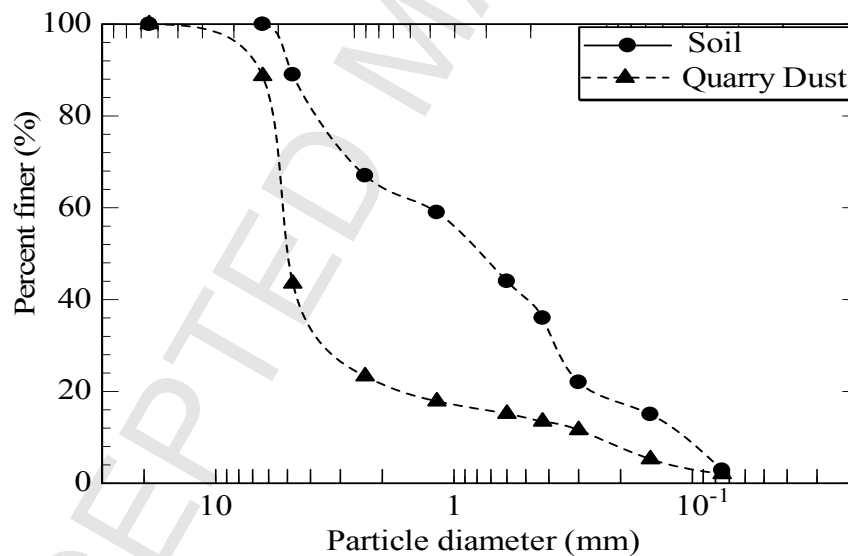
Soil preliminary test results

Soil Property	NMC (%)	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (g/cm ³)	G_s	$G_{s(QD)}$	AASHTO Soil Class
Test Result	12.1	40	18	22	13.1	1.76	2.6	2.71	A-2-7

Table 2

Particle Size Distribution (PSD) of Soil and Quarry Dust (QD)

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	-	100	89	67	59	44	36	22	15	2.85	0
Quarry dust	100	88.7	43.5	23.3	17.85	15.15	13.45	11.6	5.25	2.0	0

**Fig. 2.** Grading curves of the lateritic soil and the quarry dust

The aluminosilicate concentration and cementitious potentials of the soil, OPC and the QD, which fulfilled that material cohesion, is a factor as very important in soil additive blending and stabilization is presented in Table 3. Material requirement for cementitious materials is that the sum of the percentage composition of SiO_2 , Al_2O_3 , and Fe_2O_3 should be 70% and above. The result of the analyzed samples in Tables 3 show that the sum total of the percentage of SiO_2 , Fe_2O_3 , and Al_2O_3 is 82.97% for QD which is greater than 70%, which makes the QD a highly cementitious material (ASTM C618, 1978). This behaviour was of great advantage because it

gave a high level of interaction and binding between the test soil sample and the admixture (QD). Secondly, the compounds as presented in Table 3 show that the test soil had the metallic oxides; lime, that ensured hydration, and many more that ensured cation exchange and pozzolanic reaction and the formation of floccs like SiO_2 , Al_2O_3 and Fe_2O_3 . The low content of MgO shows that the soil has a very slim tendency to form the brucite sheets; the octahedral sheets formed with the replacement of Aluminium atom by Magnesium atom.

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
Lateritic Soil	76.56	15.09	2.30	2.66	0.89	2.10	0.33	0.07	-	-	-	-	-
QD	63.48	17.72	5.56	1.77	4.65	2.76	0.01	3.17	0.88	-	-	-	-
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

QD: Quarry Dust

DOPC: Dangote Ordinary Portland cement

3.1 Repulsion Potential, Dielectric and Compaction of Test Soil

The results of the effect of lateritic soil treatment with quarry dust were presented in Tab. 4. The dry density of the stabilized test soil improved consistently under the addition of QD material at a constant DOPC percentage of 5%. It is only understandable that the consistent increase in MDD recorded and sketchily presented in Fig 3a, is as a result of the high relative density of the QD compared to the soil. However, there was a potential that the formation of new compounds occurred, which obviously led to the increase in the maximum dry density (MDD) at the increased quantity of QD and also due to molecular rearrangement of the released cations in the formation of transitional compounds within the adsorbed complex, which showed high densification at QD variation. The cementing behaviour of the test soil and QD may have caused the reduced OMC due to the high heat of hydration and also less demand for water by various cations and the clay mineral particles from both test soil sample and admixture to also undergo the hydration reaction as sketchily presented in Fig 3b. This was as a result of the increased reactive oxides within the adsorbed complex and the pozzolanic behaviour of the QD mixed with the lateritic soil, thereby achieving higher dry density at lower water content. This behaviour may also be due to cation exchange reactions between the cations released by the additive and

those from test soil and the admixture occupying the void spaces thereby improving the porosity of the soil matrix and in addition, the flocculation and agglomeration of the clay particles due to the exchange of ions (Osinubi et al. 2009; Hausmann, 1990; Nnochiri and Ogundibe, 2016). The behaviour corroborates the results reported by Osinubi et al. (2009). An explanation that was offered for this behaviour was that there was increased desire for water, which accounted for the higher amount of additives because more water was required for the dissociation of admixtures into Ca^{2+} and OH^- ions to supply more Ca^{2+} for the cation exchange reaction. The reduction in the optimum moisture content (OMC) with increased proportions of admixture content and also the decrease in dielectric constant and the repulsion potential with respect to x might be due to cation exchange, that caused the flocculation and steady densification of clay particles. Moreover, the QD is a highly pozzolanic material and requires water for hydration thereby improving the strength development of the QD + Soil matrix. Fig. 3c presents that dielectric constant reduced with increased QD and increased with increased OMC. This also corroborates with the findings of Hausmann (1990) and Artkins et al (1998) that moisture is drawn to the cathode of the Reuss experimental set up while the dielectric increased as a result. This is due to also the direct relationship between dielectric constant and water as electrolyte. Figs. 3d and 3e show the behaviour of repulsion potential (RP) with QD and OMC. The OMC reduced and MDD increased with increased QD. RP decreased with increased QD. These behaviours were due to the release of cations by the binder (DOPC), the additive oxides (i.e. oxides from QD) and water, which contributed to hydration reaction, cation exchange reaction, pozzolanic reaction, carbonation reaction, etc. and consequently the formation of flocs and electrodensification. Dielectric constant decreased with a decrease in RP, which corroborates with the findings of Hausmann (1990) and Das (2003; 2008; 2010; 2011), Nnochiri and Ogundibe (2016) and Das and Sobhan (2012) that during electrodensification and electrostabilization, which are processes in electrokinetics, cations rearrange and form a quasi complex which reduces the RP of the released cations as shown in Fig. 4 and consequently bring them close to one another to react. During this process of rearrangement, the dielectric constant reduces with RP and densification and long term strength development is encouraged.

Table 4

Effect of OPC+QD on the Repulsion Potential, Dielectric Constant and Compaction of Stabilized Soil

Items	QD wt %										
	0	5	10	15	20	25	30	35	40	45	50
OMC (w), %	13.1	13	12.4	12	12	11.5	11.4	11.1	10	10	10
MDD (ρ), g/cm ³	1.76	1.87	1.94	2.01	2.31	2.42	2.50	2.59	2.70	3.12	3.12
Dielectric (λ)	117.7	109.1	94.5	90.7	76.2	69.8	61.1	49.5	40.1	32.2	32.2
C ($\times 10^{-12}$) (F)	84.41	78.24	67.73	65.05	64.65	50.06	43.82	35.50	28.76	23.09	23.02
$\frac{\Phi(x)}{x^2}$	0.094	0.108	0.129	0.139	0.190	0.218	0.257	0.329	0.423	0.609	0.609

*C = capacitance in Farad (F)

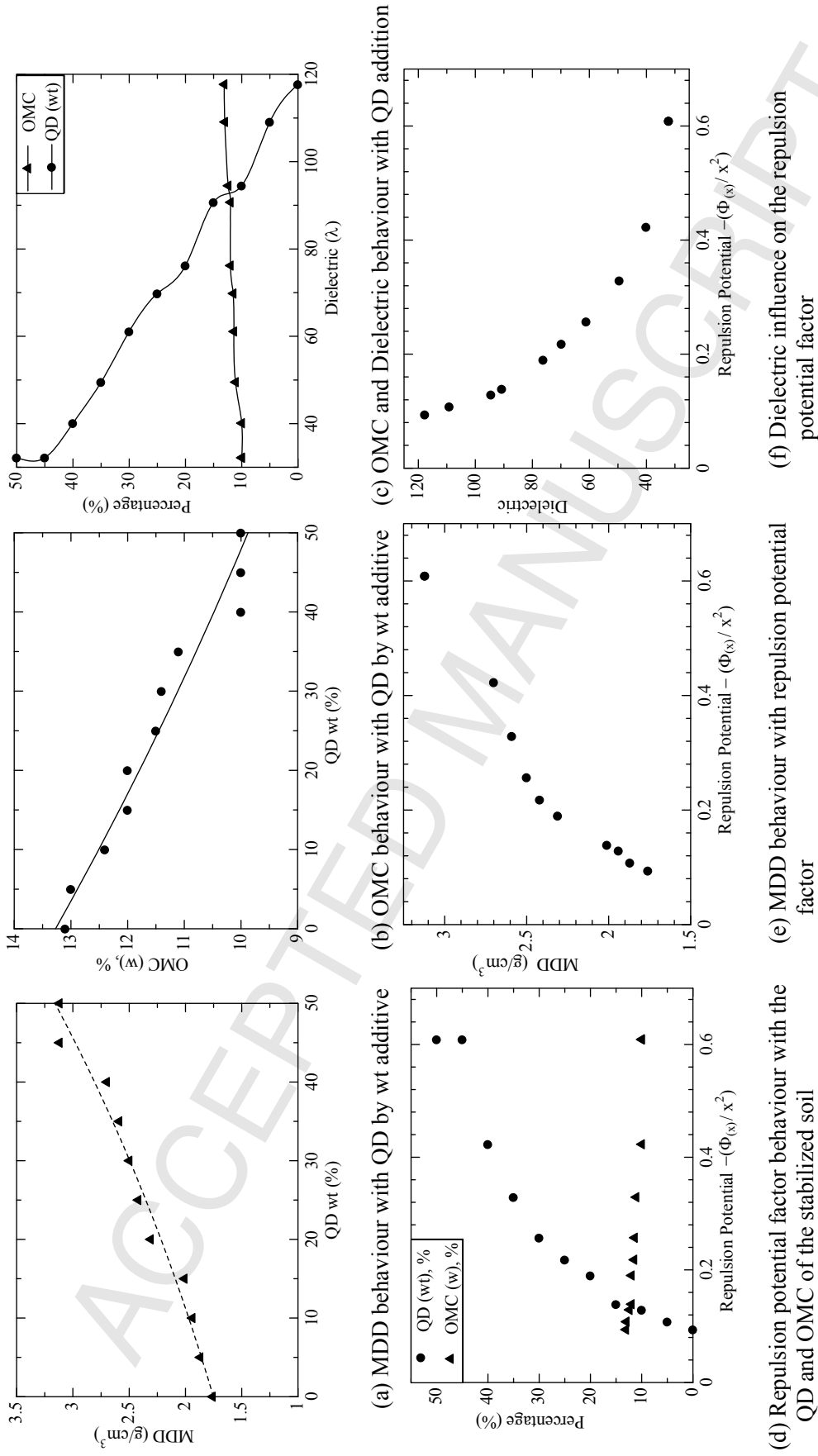


Fig. 3. Effects of OPC+QD on the Repulsion Potential, Dielectric Constant and Compaction of Stabilized Soil.

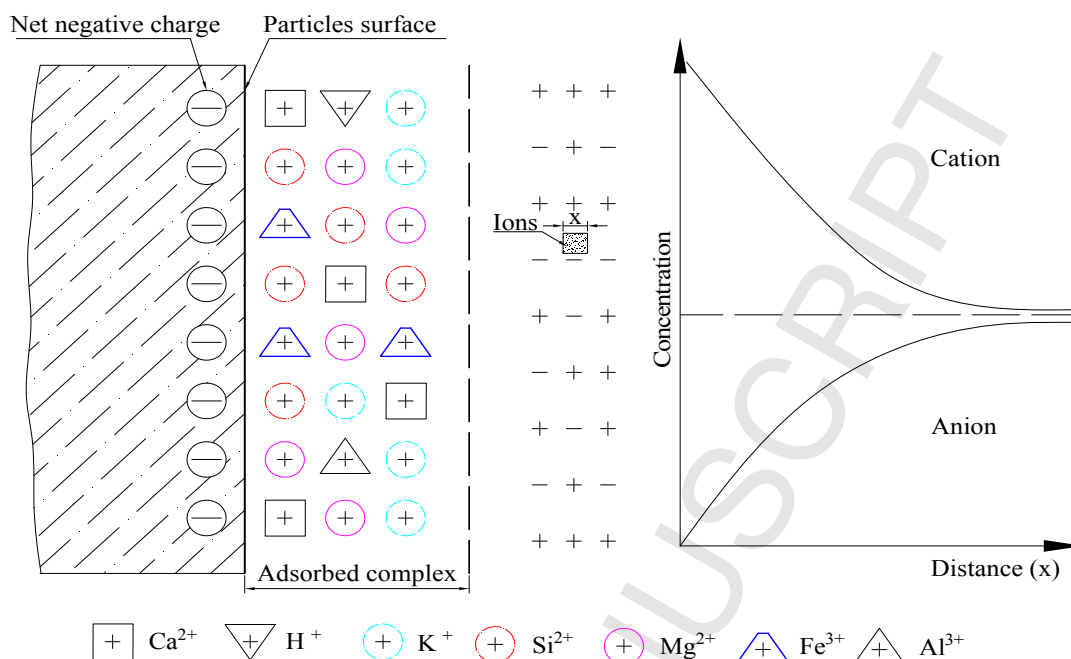


Fig. 4 Release of ions and cations migration and exchange reaction in the adsorbed complex and the repulsion potential of the treated lateritic soil

3.2 The Effect of Cation Distance from the Clay Particle Surface on Repulsion Potential

The behaviour of the repulsion potential (RP) with the distance of the cations from the surface of the clay particle is presented in Tab. 5 and Fig. 5. It is important to note that (as shown in Fig. 4) at the adsorbed complex, the cations are highly viscous and not free ions because they take part in the stabilization reaction protocol. Beyond the adsorbed complex, the cations are free to move and can be affected by the repulsion potential (RP). The higher the gap between the ions and the clay particle surface, the higher the RP. But the stabilization operation with OPC, QD and water has improved the strength properties of the stabilized test soil by decreasing the distance between the released cations and the charged clay particle surface and hence the adsorbed complex. So from Fig. 5, the RP increased at higher distances between particles and ions and decreased at increased QD by weight proportion (Hausmann, 1990; Das, 2003). This behavior is attributed to the improved porosity of the treated soil due to the varied increase in the quantity of the QD,

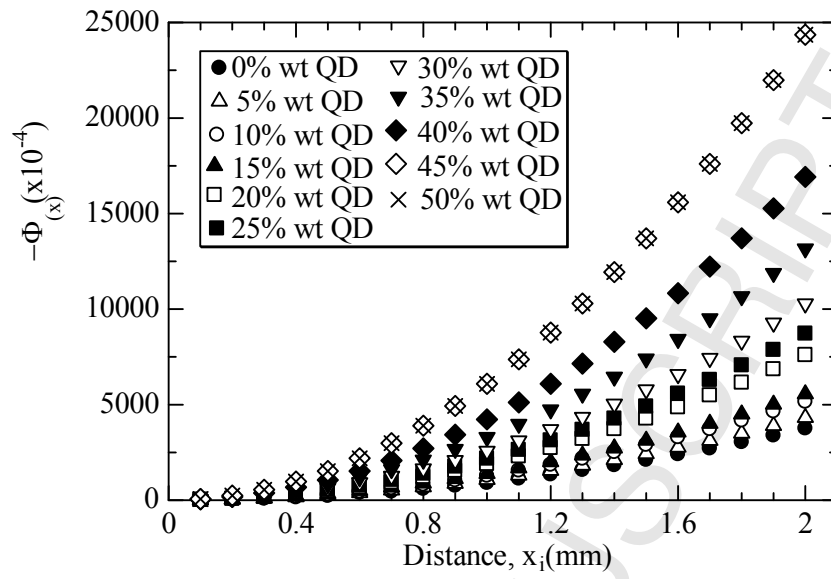


Fig. 5. Effects of Distance (x) on the Repulsion Potential of OPC+QD Stabilized Soil

Table 5

Effect of Distance (x) on the Repulsion Potential of OPC+QD Stabilized Soil

$\Phi_{(x)}$ @ %wt QD ($\times 10^{-4}$)	x_j (mm)																			
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
0%	9.4	37.6	84.5	150.4	235	388.4	460.6	601.6	761.4	904	1137.4	1353.6	1588.6	1842.4	2115	2406.4	2716.6	3045.6	3393.4	3760
5%	10.8	43.2	97.2	172.8	270	388.8	529.2	691.2	874.8	1080	1306.8	1555.2	1825.2	2116.8	2430	2764.8	3121.2	3499.2	3898.8	4320
10%	12.9	51.6	116.1	206.8	322.5	464.4	632.1	825.6	1044.9	1290	1560.9	1857.6	2180.1	2528.4	2902.5	3302.4	3728.1	4179.6	4656.9	5160
15%	13.9	55.6	125.1	222.4	347.5	500.4	681.1	889.6	1125.9	1390	1681.9	2001.6	2349.1	2724.4	3127.5	3558.4	4017.1	4503.6	5017.9	5560
20%	19	76	171	304	475	684	931	1216	1539	1900	2299	2736	3211	3724	4275	4864	5491	6156	6859	7600
25%	21.8	87.2	196.2	348.8	545	784.8	1068.2	1395.2	1765.8	2180	2637.8	3139.2	3684.2	4272.8	4905	5580.8	6300.2	7063.2	7869.8	8720
30%	25.7	102.8	231.3	411.2	642.5	925.2	1259.3	1644.8	2081.7	2570	3109.7	3700.8	4343.3	5037.2	5782.5	6579.2	7427.3	8326.8	9277.7	10280
35%	32.9	131.6	296.1	526.4	822.5	1184.4	1612.1	2105.6	2664.9	3290	3980.9	4737.6	5560.1	6448.4	7402.5	8422.4	9508.1	10659.6	11876.9	13160
40%	42.3	169.2	380.7	676.8	1057.5	1522.8	2072.7	2707.2	3426.3	4230	5118.3	6091.2	7148.7	8290.8	9517.5	10828.8	12224.7	13705.2	15270.3	16920
45%	60.9	243.6	548.1	974.4	1522.5	2192.4	2984.1	3897.6	4932.9	6090	7368.9	8769.6	10292.1	11936.4	13702.5	15590.4	17600.1	19731.6	21984.9	24360
50%	60.9	243.6	548.1	974.4	1522.5	2192.4	2984.1	3897.6	4932.9	6090	7368.9	8769.6	10292.1	11936.4	13702.5	15590.4	17600.1	19731.6	21984.9	24360

4. Concluding Remarks

The behaviour of the RP and released cations in the adsorbed complex with the DOPC + QD stabilized test lateritic soil has been studied through materials preparation and laboratory examinations and the results can be concluded with the following remarks;

- (i) The DOPC+QD treatment of the test lateritic soil reduced the dielectric with a reduction in the adsorbed moisture and increased matrix dry density at a consistent reduction in the repulsion potential (RP).
- (ii) The addition of QD by weight in varied proportion increased the strength properties by reducing the distance x between the released cations of the adsorbed complex and the surface of the clay particle and consequently keeping the RP reduced for long term densification and strength development.
- (iii) The results of the research have presented to its minute detail and micro level what reactions that take place within the adsorbed complex in a stabilization exercise and the effective contribution of QD to the results achieved.
- (iv) Finally, QD proved to be a good admixture in the stabilization of weak lateritic soils for construction purposes and for use as subgrade and subbase material in transportation geotechnics.

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