

Nanostructured Waste Paper Ash Treated Lateritic Soil and Its California Bearing Ratio Optimization

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Abstract

The stabilization potentials of NWPA and the CBR optimization were investigated on the treated olokoro lateritic soil. The soil was classified as an A-2-7 soil according to AASHTO classification method. From the stabilization procedure, it has been found that the admixture improved the strength characteristics of the stabilized lateritic soil for use as base material in pavement construction. With the laboratory results, a nonlinear regression relationship was formulated through the multiple regression algorithms for the California bearing ratio (R) as a dependent variable with optimum water content (w), maximum dry density (D), and percentage by weight additive of NWPA (SA) as the independent variables. The nonlinear relationship was linearized to enable the optimization operation with Simplex Linear Programming (Optimization) to be conducted. This iteration procedure was conducted and the results showed that the CBR (R) was optimized at $R_{max}=219.16\%$ with $x_1=48.103$, $x_2=4.833$, $x_3=13.45$, and $x_4=0.948$ in the stabilization of lateritic soils with NWPA as an admixture applied in the percentages of 0, 3, 6, 9, 12, and 15%.

Keywords: Optimization; Lateritic Soils; Geotechnical Engineering; Soil Stabilization; Waste Paper Ash; Soil-Ash Interaction

Introduction

The mathematical operation of obtaining the optimal maximum and optimal minimum of the effect of a process or procedure in an engineering mechanism is called optimization [1-6]. In the field of geotechnical engineering and the area of soil stabilization and improvement in particular, the primary target is the achievement of the lateritic soil strength properties that will ensure the durability and safety of civil engineering projects founded on soils [7-9]. In the developing world for instance, road pavement decay resulting from failed subgrade and sub base layers is one of the major problems bedeviling the traffic facilities [10-12]. A proper geotechnical construction is one that ensures that the proper steps are taken to embark on a comprehensive soil exploration that will give information on the strength of the underlying soil [13,14]. With this technical background, the geotechnical expert plans a soil stabilization technique suitable for the studied soil to ensure that the bearing capacity of the soil is improved upon before structures are constructed or pavement layers are laid upon the subgrade soil [7,12,14]. In recent times, additives and geosynthetics apart from known cementations materials have been in use in the stabilization of the subgrade lateritic soils which included bagasse ash, snell shell ash, coconut shell ash, palm kernel shell ash, palm bunch ash, waste paper ash, etc. [7,13,15-20]. Researchers have also shown that some of these additive substances in their amorphous ash form possess cementing properties because of the alumina-silica composition which classify them as pozzolanas [21-23]. The optimization of the properties of the lateritic soils treated with these additives has been researched upon in recent times employing different mathematical approaches to reduce the task involved in making decisions and studying the performance of these constructed facilities. Keying into the laboratory and analytical results obtained by previous researchers, an optimization model has been developed to obtain the maximum or minimum percentage of the waste paper ash needed to achieve the optimal of California bearing ratio of the treated lateritic soil matrix. Hence the main aim of this research exercise was to develop an optimization model of the CBR of soils treated with nanostructured waste paper ash with the following specific objectives; (i) to evaluate the stabilization potentials of nanostructured waste paper ash [15] and (ii) to develop the CBR optimization model

for the NWPA treated lateritic soil using the simplex method of linear programming SLP 1.

Technical Approach

The technical approach was carried out in three phases; preparation of materials (lateritic soil and waste paper ash), laboratory exercises [15] and formulation of the parametric equations and models of the results and the application of the nonlinear multiple regression relationship and the simplex linear programming (SLP) [1,2,4,24-28].

Materials

Waste paper was collected from various dump sites and educational institutions within Abia, Imo and Enugu states. The collected solid wastes were sun-dried openly for one week to remove moisture, completely burnt, and completely pulverized manually and with a mechanical grinder. The ash dust was sieved with a 200nm Nano sieve; UV/VIS Spectrophotometer test at 25°C characterization was conducted on the ash to determine its absorbance and average particle size and stored for the laboratory investigation. This was used in the proportions of 3%, 6%, 9%, 12% and 15% by weight to treat the lateritic soil. Ordinary Portland cement was used as a binder at a fixed percentage of 5% (ASTM c150). Lateritic soil sample used for this study was collated from a borrow pit located at Olokoro, on latitude of 05°28'36.700" North and longitude 07°32'23.170" East from a depth of 2 meters, a distance of 5km off Ubakala road from the Ishi Court junction, Umuahia, Abia state capital, Nigeria. The sample collected

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was in solid state and reddish brown in color. The soil obtained from this location was air dried in trays for six days.

Laboratory methods

The following preliminary tests were conducted; Sieve Analysis Test in accordance with BS 1377-2 (1990); this was conducted with vertically arranged sieve sizes mounted on an automatic shaker, Compaction Test (Standard Proctor Test) in accordance with BS 1377-2 and BS 1924; this was conducted with 2016 ELE Automatic Compactor Machine, California Bearing Ratio Test (CBR) in accordance with BS 1377-2 and BS; 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, Atterberg Limit Test; was conducted using a 2013 cassagrande apparatus, Unconfined Compressive Strength(UCS) Test in accordance with BS 1377-2 and BS 1924 was conducted with a 2015 Load Trac III load frame apparatus, Specific Gravity Test was conducted by Pycnometer method and Chemical Composition Test on the natural soil sample and results were obtained.

Parametric formulation

This model studies the regression relationship on the stabilized laterite-ash mixture between the California bearing ratio (CBR); the dependent variable and water content (w), maximum dry density (D) and additive sample percentage by weight proportion (S_A). These are the independent variables in this model. The relationship between these variables is a nonlinear objective function of the form,

$$y = K X^\beta W^{\beta_2} Z^{\beta_3} \quad (1)$$

Where X, W and Z are the independent variables and K, β , β_2 and β_3 are regression constants. Equation 10 can be linearized by taking the logarithm of the equation as follows,

$$\text{Log}(y) = \text{Log}(K) + \beta_1 \text{Log}(X) + \beta_2 \text{Log}(W) + \beta_3 \text{Log}(Z) \quad (2)$$

The evaluation of the coefficients of Equation 2 can be obtained by setting;

$$\text{Log}(y) = Y_i; \text{Log}(K) = \beta_0; \text{Log}(X) = x_1; \text{Log}(W) = x_2; \text{Log}(Z) = x_3 \quad (3)$$

The linear multiple regression relationship arising from the above model is of the general form;

$$Y_i = \beta_0 + \beta_1 x_{1(i)} + \beta_2 x_{2(i)} + \beta_3 x_{3(i)} + \epsilon_i; i = 1, 2, 3, \dots, n \quad (4)$$

Where,

Y_i = represents the California bearing ratio (R)

x_1 = represents the optimum moisture content (w)

x_2 = represents the maximum dry density (D)

x_3 = represents the percentage by weight of the additive (S_A)

ϵ = error

Eq. 4 is a linear multiple regression relationship for four variables in a CBR model required to achieve the sub-grade strength at the density obtained at optimum moisture content that meets the stabilized material requirement as stipulated in the design standards for stabilized sub-grade materials. If the least square sum is also minimized in this case for the population of the results, the following equations are obtained from Eq. 4;

$$\begin{aligned} \sum Y &= \beta_0 n + \beta_1 \sum \chi_1 + \beta_2 \sum \chi_2 + \beta_3 \sum \chi_3 \\ \sum Y \chi_1 &= \beta_0 \sum \chi_1 + \beta_1 \sum \chi_1^2 + \beta_2 \sum \chi_1 \chi_2 + \beta_3 \sum \chi_1 \chi_3 \\ \sum Y \chi_2 &= \beta_0 \sum \chi_2 + \beta_2 \sum \chi_1 \chi_2 + \beta_2 \sum \chi_2^2 + \beta_3 \sum \chi_2 \chi_3 \\ \sum Y \chi_3 &= \beta_0 \sum \chi_3 + \beta_2 \sum \chi_1 \chi_3 + \beta_2 \sum \chi_2 \chi_3 + \beta_3 \sum \chi_3^2 \end{aligned} \quad (5)$$

Eq. 5 can be translated to a matrix of the general form, $AX = B$ thus;

$$\begin{bmatrix} \sum Y \\ \sum Y \chi_1 \\ \sum Y \chi_2 \\ \sum Y \chi_3 \end{bmatrix} = \begin{bmatrix} n & \sum \chi_1 & \sum \chi_2 & \sum \chi_3 \\ \sum \chi_1 & \sum \chi_1^2 & \sum \chi_1 \chi_2 & \sum \chi_1 \chi_3 \\ \sum \chi_2 & \sum \chi_1 \chi_2 & \sum \chi_2^2 & \sum \chi_2 \chi_3 \\ \sum \chi_3 & \sum \chi_1 \chi_3 & \sum \chi_2 \chi_3 & \sum \chi_3^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} \quad (6)$$

By solving Eq. 6 by Gauss Reduction Method [2], β_0 , β_1 , β_2 and β_3 can be determined and having determined the regression constants from the solution of the global matrix Eq. 6, the linear regression relationship involving CBR, moisture content (w), dry density (D) and additive sample % by weight proportion with all the other factors of the laboratory test condition being constant, can be described as;

$$\text{CBR}_i = \beta_0 + \beta_1 w_i + \beta_2 D_i + \beta_3 S_{A(i)}; i = 1, 2, 3, \dots, n \quad (7)$$

The simplex linear programming (SLP) will be applied on the objective function that would result from equation 6 and the constraints that would result from Eq 5 to optimize the California bearing ratio of the NWPA stabilized lateritic soil to obtain the optimal maximum to be attained in the stabilization of the soil using nanostructured waste paper ash additive. The simplex method is an iterative operation which strictly follows the following steps; (1) choose the most negative result in the index row formed by the objective function of the problem to determine the key row, (2) divide the entries in the 'b' column by the corresponding positive entries in the key column. The smallest quotient determines the key row, (3) the entry at the intersection of the key row and column is the pivot, (4) divide each entry in the key row by the pivot to reduce the pivot to a unit pivot. This revised row becomes the main row, (5) use this main row to operate on the remaining rows to reduce all the other entries in the key column to zero and generate new set of entries in other rows by 'new entry equals current entry minus the product of the corresponding entries in the key row and key column (6) repeat the steps above until no negative entry remains in the index row [1]. At the final iteration, the index row will be left with the optimal maximum at the constant column 'b'. The problem variables will as well have their optimized values at the constant column at which the objective function was optimized [1].

Results and Discussions

Tables 1 and 2 are the results of the preliminary test and stabilization test respectively conducted on the lateritic soil treated with NWPA added in 0, 3, 6, 9, 12 and 15% by weight of the dry sample. From Table 1, it can be deduced that the soil was classified as an A-2-7 soil according AASHTO classification system. Also the soil was a highly plastic soil prior to the stabilization exercise.

Figures 1-3 show the grading curve of the lateritic soil, the absorbance curve of the UV/VIS Spectrophotometer characterized soil and the UV/VIS Spectrophotometer characterized NWPA respectively. Figure 1 shows a well graded lateritic soil.

From the laboratory results in Table 2, the variables of Eq. 3 can be determined as follows;

$$\begin{aligned} \sum Y &= \sum \text{CBR} = 87; \sum x_1 = \sum w = 78.5; \sum x_2 = \sum D = 10.82; \sum x_3 = \sum S_A = 45; \sum \chi_1^2 = 19.52 \sum x_1 x_2 = 141.35; \sum x_1 x_3 = 608.31; \sum x_2 x_3 = 81.03; \end{aligned}$$

Property	% passing No.200 sieve	NMC (%)	w _L (%)	w _p (%)	I _p (%)	G _s (%)	AASHTO	OMC (%)	MDD (g/cm ³)	CBR (%)	Color
Results	25.4	10	47	25.15	21.85	2.67	A-2-7	13	1.84	14	Reddish brown

Table 1: Preliminary test results on the Lateritic soil.

NWPA (S _a) %	0	3	6	9	12	15
CBR (R) %	14	8	12	19	23	11
MDD (D) g/cm ³	1.84	1.76	1.77	1.85	1.84	1.76
OMC (w) %	13	13.07	12.55	10.81	13.18	15.89

Table 2: Lateritic Soil-NWPA Matrix Stabilization Results.

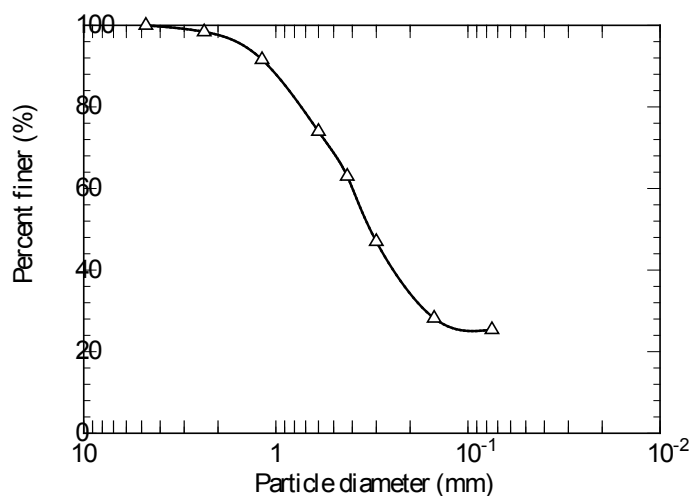


Figure 1: Particle size distribution curve of Umuntu Olokoru lateritic soil sample (Onyelowe, 2017a; Onyelowe, 2017b and Onyelowe, 2017c).

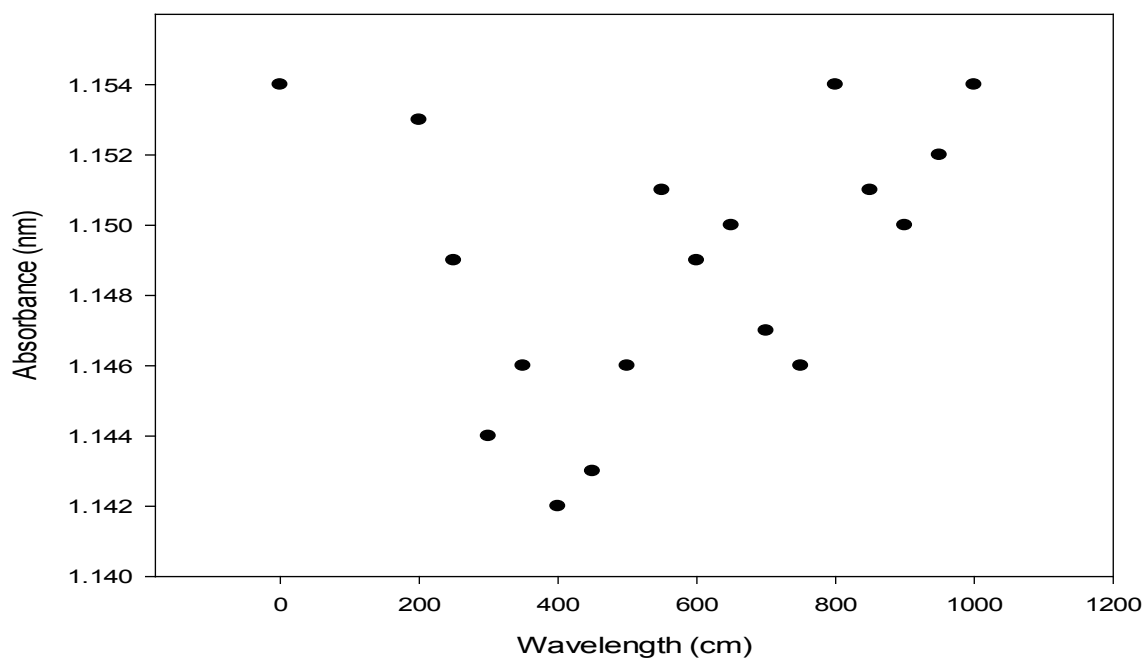


Figure 2: Variation of Absorbance against wavelength for the lateritic soil using UV/VIS Spectrophotometer at 250C (Onyelowe, 2017a; Onyelowe, 2017b and Onyelowe, 2017c).

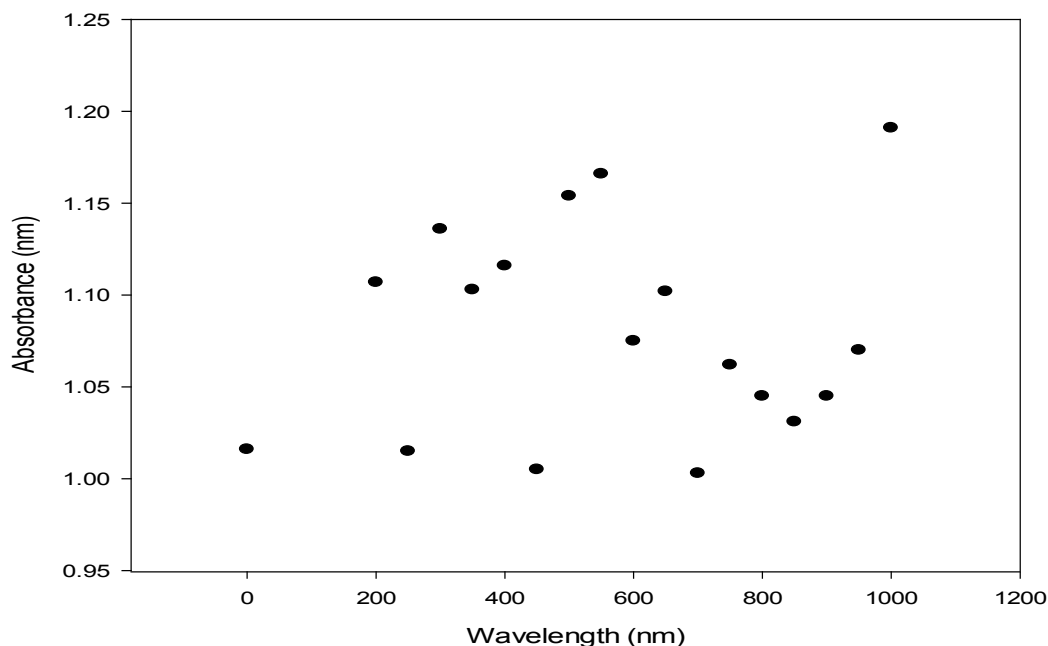


Figure 3: Variation of Absorbance against wavelength for the Nanosized Waste Paper Ash particles using UV/VIS Spectrophotometer at 250C (Onyelowe, 2017a; Onyelowe, 2017b and Onyelowe, 2017c).

Iteration	Basis	X ₁	X ₂	X ₃	X ₄	W ₁	W ₂	W ₃	W ₄	b _i	Check
1 st	w ₁	6	78.5	10.82	45	1	0	0	0	87	228.32
	W ₂ ^{**}	78.5	1040.39	141.35 [*]	608.31	0	1	0	0	1120.48	2990.03
	W ₃	10.82	141.35	19.52	81.03	0	0	1	0	157.91	411.63
	W ₄	45	608.31	81.03	495	0	0	0	1	708	1938.34
	R _i	1.065	1.9	-19.91	-0.604	0	0	0	0	0	-17.549
2 nd	w ₁	6	78.5	10.82	45	1	0	0	0	87	228.32
	w ₂	0.56	7.36	1	4.3	0	0.0071	0	0	7.93	21.15
	w ₃	10.82	141.35	19.52	81.03	0	0	1	0	157.91	411.63
	w ₄	45	608.31	81.03	495	0	0	0	1	708	1938.34
	R _i	1.065	1.9	-19.91	-0.604	0	0	0	0	0	-17.549
3 rd	w ₁	-0.06	-1.14	0	-1.53 ^{**}	1	-0.077	0	0	1.2	-0.52
	W₂ / W₃	0.56	7.36	1	4.3	0	0.0071	0	0	7.93	21.15
	w ₃	-0.11	-2.32	0	-2.91	0	-0.14	1	0	3.12	-1.22
	W ₄ ^{***}	-0.38	11.93	0	146.57 [*]	0	-0.58	0	1	65.43	224.56
	R _i	12.21	148.93	0	85.01	0	0.14	0	0	157.89	403.54
4 th	w ₁	-0.06	-1.14	0	-1.53 ^{**}	1	-0.077	0	0	1.2	-0.52
	x ₃	0.56	7.36	1	4.3	0	0.0071	0	0	7.93	21.15
	w ₃	-0.11	-2.32	0	-2.91	0	-0.14	1	0	3.12	-1.22
	W ₄ ^{***}	-0.0023	0.081	0	1 [*]	0	-0.004	0	0.0068	0.446	1.53
	R _i	12.21	148.93	0	85.01	0	0.14	0	0	157.89	403.54

5 th	w_1	-0.063	-1.16	0	0	1	-0.0831	0	0.0104	1.88	1.821
	x_3	0.55	7.012	1	0	0	0.0243	0	-0.0292	6.012	14.571
	w_3	-0.117	-2.08	0	0	0	-0.152	1	0.02	4.42	3.23
	$-W_4 \chi_4$	-0.0023	0.081	0	1	0	-0.004	0	0.0068	0.446	1.53
	R_i	12.41	142.044	0	0	0	0.48	0	-0.578	119.976	273.48
6 th	w_1	-0.063	-1.16	0	0	1	-0.0831	0	0.0104	1.88	1.821
	x_3	0.55	7.012	1	0	0	0.0243	0	-0.0292	6.012	14.571
	W_3^{**}	0.0563	1	0	0	0	0.073	-0.48	-0.0096	-2.125	-1.553
	x_4	-0.0023	0.081	0	1	0	-0.004	0	0.0068	0.446	1.53
	R_i	12.41	142.044	0	0	0	0.48	0	-0.578	119.976	273.48
7 th	w_1	-0.0058	0	0	0	1	-0.0089	-0.488	0.00065	-0.279	0.243
	x_3	0.155	0	1	0	0	-0.488	3.366	0.0387	20.91	25.46
	$-W_3 \chi_2$	0.0563	1	0	0	0	0.073	-0.48	-0.0096	-2.125	-1.553
	x_4	-0.0069	0	0	1	0	0.073	0.039	0.00708	0.618	1.656
	R_i	4.213	0	0	0	0	-9.89	68.18	0.786	421.82	494.074
8 th	W_1^{***}	1	0	0	0	-172.41	1.53	84.138	-0.112	48.103	41.897
	x_3	0.155	0	1	0	0	-0.488	3.366	0.0387	20.91	25.46
	x_2	0.0563	1	0	0	0	0.073	-0.48	-0.0096	-2.125	-1.553
	x_4	-0.0069	0	0	1	0	0.073	0.039	0.00708	0.618	1.656
	R_i	4.213	0	0	0	0	-9.89	68.18	0.786	421.82	494.074
9 th	$-W_1 \chi_1$	1	0	0	0	-172.41	1.53	84.138	-0.112	48.103	41.897
	x_3	0	0	1	0	26.724	-0.725	-9.675	0.0555	13.45	18.966
	x_2	0	1	0	0	9.7069	0.0644	-5.217	-0.0033	4.833	-3.912
	x_4	0	0	0	0	-1.183	0.0835	0.616	0.0063	0.948	1.9434
	R_i	0	0	0	0	726.38	-16.336	-286.3	1.2579	219.16	317.562

*** is key row; ** is key column and * is pivot; $w_1, w_2, w_3,$ and w_4 are slack variables heading the unity matrix while $x_1, x_2, x_3,$ and x_4 are problem variables

Table 3: The Simplex Linear Optimization Program for the Optimized CBR of the NWPA Stabilized Lateritic Soil.

$$\sum \chi_2^2 = 19.52; \sum \chi_3^2 = 495; \sum Yx_1 = 1120.48; \sum Yx_2 = 157.91; \sum Yx_3 = 708; n = 6 \quad (8)$$

Substitute the variables of Eq. 8 into Eq. 5;

$$\begin{bmatrix} 87 \\ 1120.48 \\ 157.91 \\ 708 \end{bmatrix} = \begin{bmatrix} 6 & 78.5 & 10.82 & 45 \\ 78.5 & 1040.388 & 141.35 & 608.31 \\ 10.82 & 141.35 & 19.52 & 81.03 \\ 45 & 608.31 & 81.03 & 495 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix}$$

Solving Eq. 9 with Gauss Reduction Method [2], the regression constants were determined as follows;

$$\beta_0 = -1.065; \beta_1 = -1.9; \beta_2 = 19.91 \text{ and } \beta_3 = 0.604 \quad (10)$$

The objective function of the optimization operation is given in Eq. 11,

$$R + 1.065x_1 + 1.9x_2 - 19.91x_3 - 0.604x_4 = 0 \quad (11)$$

While the constraints equations are Eqs. 12, 13, 14 and 15;

$$6x_1 + 78.5x_2 + 10.82x_3 + 45x_4 = 87 \quad (12)$$

$$78.5x_1 + 1040.388x_2 + 141.35x_3 + 608.31x_4 = 1120.48 \quad (13)$$

$$10.82x_1 + 141.35x_2 + 19.52x_3 + 81.03x_4 = 157.91 \quad (14)$$

$$45x_1 + 608.31x_2 + 81.03x_3 + 495x_4 = 708 \quad (15)$$

The SLP was formulated and sequentially solved through series of iterations to achieve the optimized California bearing ration as shown in Table 3.

$$R_{\max} = 219.16\% \text{ with } x_1 = 48.103, x_2 = 4.833, x_3 = 13.45, \text{ and } x_4 = 0.948$$

From the practical exercise, the California bearing ratio reduced with the addition of 3% of NWPA. This property increased again with the addition of 6% NWPA but still less than the preliminary result at 0% NWPA. At 9% addition of NWPA, the California Bearing Ratio property increased further and the maximum value was achieved with the addition of 12% NWPA to a value of 23%, which satisfied the material condition for use as a sub-base material. With the addition of 15% NWPA, the strength property reduced again. This behavior may be attributed to the admixture's increased reactive surface area, its highly pozzolanic behavior and lower density as a result of nanosization. With these results, the strength properties of the stabilized soil have been enhanced for use in pavements designs and construction. The soil + 12% NWPA mixtures passed to meet the minimum CBR value of 20 – 30% specified by (BS 1924, 1990) for materials suitable for use as base course materials which was determined at MDD and OMC [8,15,29,30]. This is close to the findings of Gidigas and Dogbey which stated that the minimum CBR value of 20 – 30% is required for sub-bases when compacted at OMC [31,32]. Increase in CBR, an implication of the increase observed in MDD is attributed to the compatibility of the grains of soil by the increased reactive surface by the ash pulverization and the high pozzolanic properties of the NWPA such that greater densification

was achieved [33-36]. However, the optimization operation has shown an optimized CBR at 219.16% at a moisture content of 48.103%, dry density of 4.833 g/cm³, NWPA additive percentage by weight of 13.45 and residual of 0.948. The optimized results obtained will be applied in the subgrade stabilization procedure when treated with amorphous ash materials in their nanostructured texture [37].

Conclusion

The stabilization potentials of NWPA were investigated and it has been found that the admixture improved the strength characteristics of the stabilized lateritic soil for use as base material in pavement construction. With the laboratory results, a nonlinear regression relationship was formulated through the multiple regression algorithms for the California bearing ratio (R) as a dependent variable with optimum water content (w), maximum dry density (D), and percentage by weight additive of NWPA (SA) as the independent variables. The nonlinear relationship was linearized to enable the optimization operation with Simplex Linear Programming (Optimization) to be conducted. This iteration procedure was conducted and the results showed that the CBR (R) was optimized at $R_{max}=219.16\%$ with $x_1=48.103$, $x_2=4.833$, $x_3=13.45$, and $x_4=0.948$ in the stabilization of lateritic soils with NWPA as an admixture applied in the percentages of 0, 3, 6, 9, 12, and 15%.

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