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POLYNOMIAL MODELS FOR PREDICTING TIME LIMITS FOR COMPACTION AFTER MIXING OPERATION OF LATERITIC SOIL REINFORCED USING CEMENT OR LIME

Ugochukwu Nnatuanya Okonkwo[1*], Emmanuel Chukwudi Ekeoma[1] and Linus Owo Eleke[1]

[1]Department of Civil Engineering, Michael Okpara University of Agriculture Umudike, PMB 7267, Umuahia, Abia State, Nigeria

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*Corresponding author's email: ugochukwuokonkwo75@mail.com; okonkwo.ugochukwu@mouau.edu.ng

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Abstract — The demand for natural aggregates has increased in recent years because of diverse environmental interests. Consequently, its cost has soared astronomically and the utilization of lateritic soil for low-cost roads has been an attractive option. In most cases during road construction, unprecedented conditions may lead to delays in the compaction of the treated soil after the mixing operation and placing had taken place. Thus, this study developed polynomial models for predicting time limits for compaction after mixing operation within 0-180 minutes at 30 minutes intervals for lateritic soil reinforced with cement and lime. The percentage contents by weight of the dry soil for cement or quick lime mixed with the soil were 2, 4, 6, 8 and 10%. Consistency indices tests and particle size analysis were carried out on the untreated lateritic soil for characterization. The tests conducted on the lateritic soil prepared with cement and quick lime were compaction test (Standard Proctor), California Bearing Ratio (CBR) and unconfined compressive strength (UCS) of 7 days curing. The AASHTO soil classification system and Unified Soil Classification system rated the lateritic soil to be A-6(13) and clayey soil (CL), respectively. Ordinarily, the lateritic soil was found to be a poor construction soil and therefore requires treatment to improve its strength in order to make it useful for pavement purposes. At the increase in time limits for compaction after mixing, there were reductions in compaction and strength characteristics of the lateritic soils that were prepared with cement or lime. The polynomial models developed were a good fit for predicting time limits for compaction after mixing using cement/lime contents, compaction and strength characteristics of the strengthened soil. The polynomial models gave coefficients of correlation and determination of 0.988 and 0.976, respectively, when the soil was prepared with cement whereas, in the case of lime-prepared soil, the values were 0.966 and 0.933, respectively. The cement/lime contents, optimum moisture content (OMC), CBR and UCS (7 days curing) were entirely statistically significant in predicting time limits for compaction after mixing at a 95% confidence level.

***Keywords*:** Polynomial model, time limit for compaction, low-cost road, compaction characteristic, strength characteristic

List of Notations

E = Time limits for compaction after mixing operation (minutes)

R = CBR (%)

S = UCS for7 days curing (kN/m^2)

M = OMC (%)

C = Cement content (%)

L = Lime content (%)

1.0 INTRODUCTION

Another name for lateritic soils is residual soils because they emanate from the disintegration of sedentary rocks. Formation of lateritic soils involves the consistent washing away of lighter minerals such as silicon oxide which culminates in a residue of soil that is rich in heavier minerals (sesquioxides) like iron and aluminium oxides. The majority parts of the country have basement complex rocks underneath, of which the disintegration of the basement complex results in the formation of lateritic materials that are prevalent in most regions. It is usually common in

Nigeria to encounter lateritic soil or being used as a borrowed construction material for filling especially during road construction work because they are readily available. Lateritic soils are usually non-problematic soils and very useful in civil engineering projects. Lateritic soils have been diversely utilized in various construction works in previous studies for subgrade soil, earth embankments, dams, landfill liners, road pavements [1–14]. In these recent years, the cost of natural aggregates is continuously rising such that the resulting cost of design, construction and maintenance of roads has utterly increased. Consequently, taking advantage of the cheap or locally available lateritic soil for low-cost road construction works appears to be an attractive option. Ultimately, this proposition has been beneficial in making the lateritic soils in their stabilized form to be used as low-cost pavements structures. Thus, availability of acceptable roads for accessibility of rural and urban areas would no longer be a difficult burden for Federal, State and Local authorities to achieve.

During construction of road pavements in the field with cement stabilized materials, construction specifications usually stipulates that compaction should successively take place quickly after mixing, placing and shaping are accomplished because of the rapid take-off of hydration reaction as soon as water is being added to the soil-cement matrix. It is through this hydration reaction that the cement-stabilized materials gain their strength. In many occasions in the site, unprecedented conditions like when construction workers are wounded, stoppage of construction machines due to fault and other issues that frequently occur could lead to elapse of time before the compaction could be carried out. It has been noted that increase in time limits before compaction decreased consistency indices, cohesion and internal friction angle as confirmed in [15]. Previous studies on time limits for compaction after mixing operation for cement stabilized materials had indicated that delay in compaction reduced the strength and compaction characteristics (maximum dry density) of the stabilized soils [16–18]. Conversely, [19] opined that there are benefits derived from increasing the time limits for compaction after mixing when lime was used to stabilize soils. The scientific reason offered was that it was necessary to allow the lime-stabilized soil to 'mellow' for a period to enable the lime hydrate in order to totally diffuse through the soil, therefore resulting in maximum ability of plasticity. During the mellowing period, compaction could be a way of decreasing carbonation and evaporation. Thus, there is a need for comparative study on time limits before compaction after mixing between cement and lime treated soil. Research works on time limits for compaction after mixing for lime and cement treated materials are relatively scanty. However, past studies had revealed that the decreases in compaction characteristics are statistically significant at 5% level irrespective of the compaction effort applied. Furthermore, the decreases in the strength characteristics are statistically significant for varying compaction efforts, lime content and curing [20]. Previous efforts on the study of time limits for compaction after mixing for stabilized soils have not been extended to formulation of predictive models except for [21] that developed geometric predictive models. The geometric models favourably predicted time limits for compaction after mixing for lateritic soil prepared with lime and quarry dust. Furthermore, soils are peculiar in their structures. This means that the possibility of two soils to be identical in all characteristics are very unlikely. For instance, two soils might be alike in consistency indices but may be entirely different in their particle sizes distribution. Inevitably, the engineering behaviours of the two soils would likely differ at mixing operation confirmed in [22]. Therefore, generalizing the results discovered on a certain soil for any other soil could perhaps be an extravagant claim.

Moreover, stabilized materials are typical example of real systems. This implies that their properties are usually not linear. Polynomial models could also be suitable for predicting time limits for compaction after mixing for stabilized materials. Therefore, this study concentrated on developing models in the polynomial form for predicting time limits for compaction after mixing for lateritic soil prepared with cement or lime. It would be needful in order to monitor or predict maximum allowable time limits for compaction after mixing operation in the construction site using lateritic soil prepared with cement and lime.

2.0 MATERIALS AND METHODS

The sample of lateritic soil used for this study was obtained from a deposit along the East West Road in Obio/Akpor Local Government Area, of Rivers State, Nigeria; using disturbed sampling technique. The coordinates of the location are 7.12^0E and 4.78^0N for longitude and latitude respectively. Ordinary Portland cement and calcium oxide (quick lime) were applied to be the binders for strength improvement. The test requirements for the purpose of characterizing of lateritic soil like the specific gravity test, consistency indices and grain size distribution were determined based on [23–25] respectively. The soil preparation was executed by initial turning carefully in the dry state the predetermined percentage contents of cement or lime in relation to the weight of the dry soil together with the soil sample that is completely pulverized until a mixture of soil and the binder of uniform colour was achieved. The water requirement for each mix was then added which was the optimum moisture content derived from the moisture-density relationships of the compaction test. The percentage contents of cement and lime applied to the lateritic soil were 2, 4, 6, 8 and 10%. The time limits compaction after mixing within 0 – 180 minutes with 30 minutes intervals were observed in every of the mixtures of soil with cement or lime. The compaction test was determined in accordance to the British Standard Light [23] where the standard Proctor mould was adopted for specimens of the soil-cement/lime mixtures and twenty-seven (27) blows were given onto each layer for three (3) layers by 2.5kg rammer. In order not to change the test conditions for unconfined compressive strength specimens, the Proctor mould was also used to prepare the specimens after which strength values obtained were multiplied by 1.04 as correction factor to satisfy the height/diameter ratio of cylindrical specimens or 150mm sides of cubic specimens for the unconfined compressive strength test as specified in [26]. Unconfined compressive strength specimens were covered properly with cellophane bags for 7 days as membrane curing. Procedure for handling the specimens for California Bearing Ratio was slightly adjusted such that the standard for Nigeria General Specification [27] was satisfied that recommends a compulsory six days curing period unsoaked for the specimens. Afterwards the specimens were being subjected to 24 hours submergence in water and was tested after they were left for 15 minutes to drain. Multiple regression approach was applied using the statistical tools from [28] to develop the predictive model of polynomial form for maximum permissible time limits for compaction after mixing.

3.0 RESULTS AND DISCUSSION

3.1 Untreated Soil Charcterization

Table 1 Preliminary tests results of the untreated soil

Soil Characteristics	Description
Colour	Reddish brown
Specific gravity	2.71
% finer than sieve No 200	84%
Liquid limit	36.09%
Plastic limit	21.32%
Plasticity Index	14.77%
Classification rating of soil in [29]	A-6(13)
Unified Soil Classification System [30]	Clayey soil (CL)
Linear Shrinkage	11.33%
Free swell	161.29%
California bearing ratio (CBR)	3.99%
Unconfined compressive strength (UCS)	163kN/m^2
Optimum moisture content (OMC)	16.9%
Maximum dry density (MDD)	1.82 Mg/m^3

The preliminary test results for untreated lateritic soil appear in Table 1 in order to characterize the soil. The lateritic soil was classified to be A-6(13) and clayey soil (CL) in the [29] and [30] respectively. The point of coincidence of the soil's liquid limit and plastic limit with the values of 36.09%, and 14.77% on the Plasticity or A-line Chart [30] fell in the region between the curves that revealed the fact that the soil possesses inorganic clay of medium plasticity. From the results in Table 1 shows 84% of the grains finer than sieve number 200 (75 µm), it can also be deduced that the soil could be referred to as a fine-grained soil with high clay content. In the Table of AASHTO classification system, the farther a soil's group to right of the Table and a greater value of group index (GI) of a soil, the poorer the soil as a material for road work. The A-6(13) classification of the untreated soil implies that the soil belongs to a soil group located almost towards the extreme right of the AASHTO classification Table and also a high value group index of 13, have identified the soil as a poor construction soil. Also the soil gave values of free swell and linear shrinkage to be at 161.29% and 11.33% respectively. This shows that the soil has considerable characteristics of volumetric changes during the wetting and drying conditions. The alternate cycles of rising and dropping of moisture content of the soil during rainy and peak drought seasons respectively, the soil has every tendency to swell or shrink which is undesirable for a construction soil because it can cause pavement failure. Furthermore, the California bearing ratio of 3.99% was quite low. This indicates low strength characteristics for the soil in the untreated state. In fact [27] specified a California bearing ratio of 10% for sub-grade soils. Therefore the lateritic soil requires to be treated with lime or cement to make it fit for road pavements structures.

3.2 Studies on Compaction Characteristics

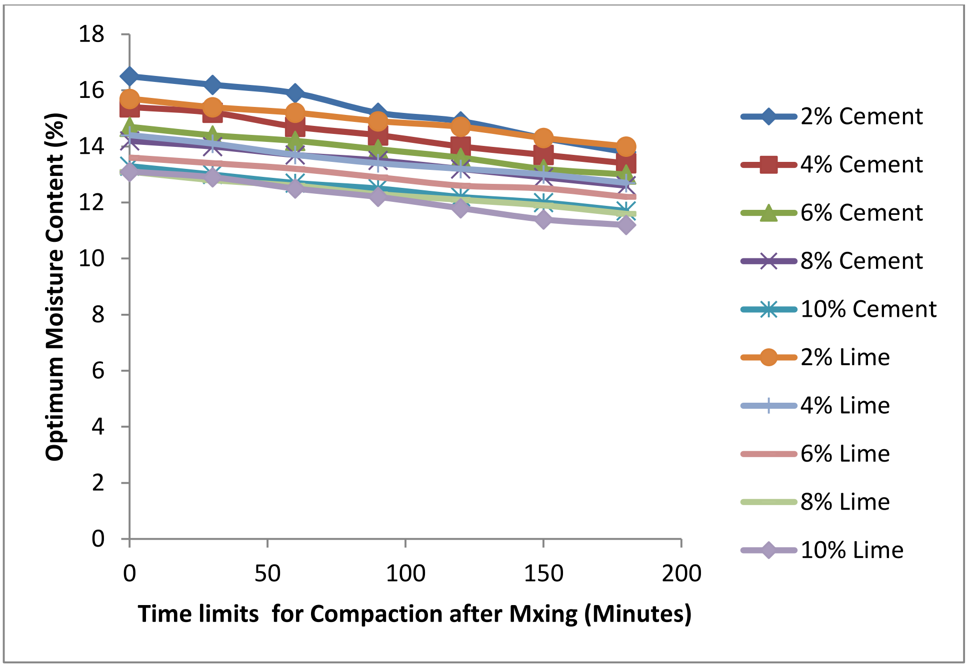

Figure 1 Plots of optimum moisture content (OMC) versus time limits for compaction after mixing of the reinforced soil

In Figure 1, the graphical representation of the relationships of the optimum moisture contents (OMC) with time limits for compaction after mixing for the prepared soil using cement/ lime. The results showed that within 0-180 minutes for time limits for compaction after mixing, the optimum moisture content reduced from 16.5 – 13.8%, 15.4 – 13.4%, 14.7 – 13%, 14.2 – 12.6% and 13.3 – 11.7% when stabilized with cement at 2, 4, 6, 8 and 10% respectively; while at 2, 4, 6, 8 and 10% lime content the reduction were 15.7 – 14%, 14.4 -12.7%, 13.6 – 12%, 13.1 – 11.6% and 13.1 – 11.2% respectively. This trend of reduction of OMC with gradual rise in compaction delay the stabilized soil was not in conformity with [16, 17], which found out that OMC rose continually as the time limits for compaction after mixing increased. Reduction trend of OMC might also be associated with the fact that the soil contains large amount of finer particles (84% as shown in Table 1) and continually required greater amount of water to sufficiently lubricate the soil grains to form clusters of the soil-cement/lime mixtures. However with increments in the time limits for compaction after mixing, the clusters formed from the prepared soil somewhat behaved in a similar manner as a coarser soil which dropped the water requirement during compaction.

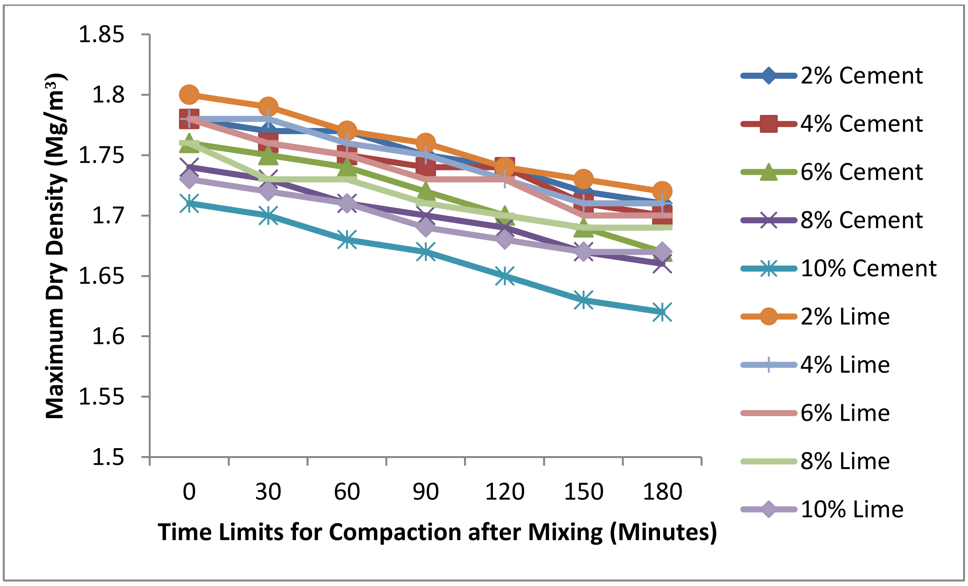

Figure 2 Plots of maximum dry density (MDD) versus time limits for compaction after mixing of the reinforced soil

Figure 2 has the pictorial view of the changes in maximum dry densities and time limits for compaction after mixing when the soil was treated with cement or lime. The results indicated that within 0-180 minutes time limits for compaction after mixing, the maximum dry density decreased from 1.78 -1.71 Mg/m^3, 1.78 -1.70 Mg/m^3, 1.76 - 1.67 Mg/m^3, 1.74 – 1.66 Mg/m^3 and 1.71 – 1.62 Mg/m^3 when stabilized with cement at 2, 4, 6, 8 and 10% respectively. While at 2, 4, 6, 8 and 10% lime content the reduction were 1.80 – 1.72 Mg/m^3, 1.78 -1.71 Mg/m^3 , 1.78 -1.70 Mg/m^3, 1.76 – 1.69 Mg/m^3 and 1.73 – 1.67 Mg/m^3 respectively. This trend of reduction in MDD as time limits for compaction after mixing continually increased for the stabilized soil is in conformity with the usual trend in the previous studies [16–18]. The drop in maximum dry density could be attributed to the fact that at a given compaction effort, some portion of the compaction ability were spent during compaction trying to disrupt the binding of the weaker clusters from the soil-cement/lime mixtures. Therefore in a fixed volume of the mould, the material content of the mould reduced which in consequent continuously reduced the density attained for the stabilized soil.

3.3 Studies on Strength Characteristics

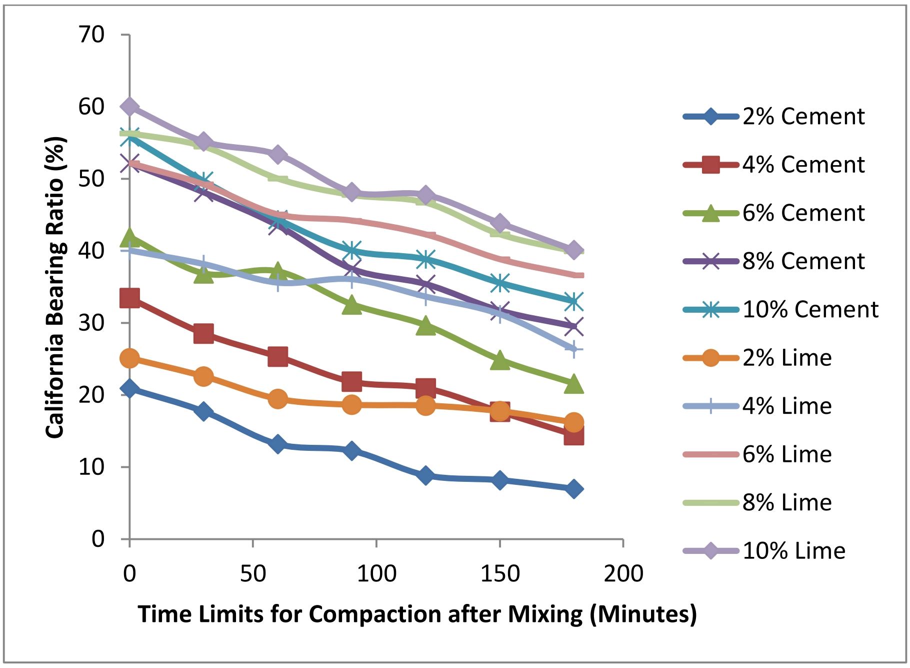

Figure 3 Plots of California bearing ratio (CBR) versus time limits for compaction after mixing of the reinforced soil

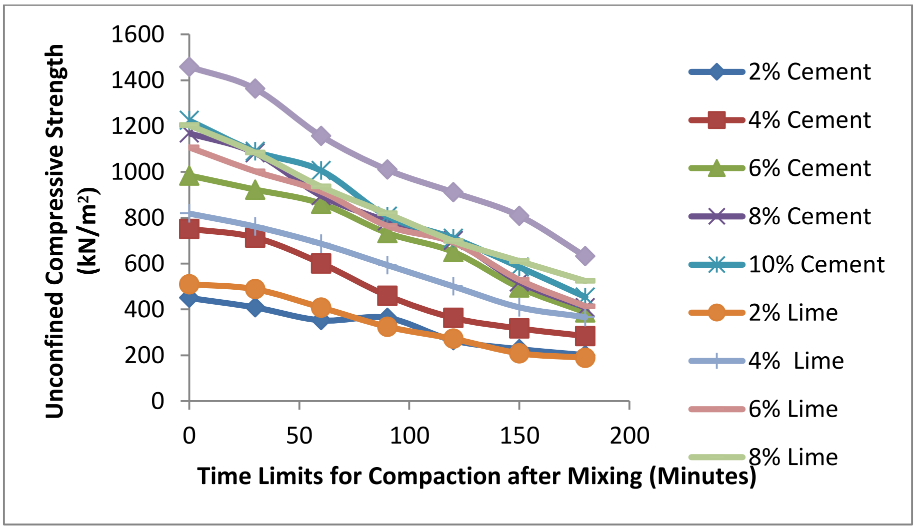

Figure 4 Plots of unconfined compressive strength (UCS) of 7 days curing versus time limits for compaction after mixing of the reinforced soil

Figures 3 and 4 is the graphical representation of the variations of California bearing ratio (CBR) and unconfined confined compressive strength (UCS) for 7 days curing respectively of the prepared soil with time limits for compaction after mixing. Figure 3 shows that within 0-180 minutes of time limits for compaction after mixing, the California bearing ratio plummeted from 20.92 -6.97%, 33.45 – 14.45%, 41.92 – 21.59%, 52.18 – 29.51% and 55.83 – 32.99% at 2, 4, 6, 8 and 10% cement content. Whereas at lime contents of 2, 4, 6, 8 and 10%, the values also plummeted from 25.11 – 16.19%, 40.05 – 26.35%, 52.18 -36.62%, 56.32 – 39.93% and 60.03 – 40.11% respectively. Likewise still within time limits for compaction after mixing of 0 – 180 minutes for the strengthened soil in Figure 4, the unconfined compressive strength (7 days curing) dropped from 450.52 – 200.18 kN/m^2, 750.92 – 283 48 kN/m^2, 984.18 – 386.64 kN/m^2, 1168.9 - 407.8 kN/m^2 and 1224.6 – 453.6 kN/m^2 at 2, 4, 6, 8 and 10% cement dosages respectively. Whereas at lime contents of 2, 4, 6, 8 and 10%, the values dropped from 510.05 – 188.93 kN/m^2, 818.93 – 365.7 kN/m^2, 1106.7 – 413.3 kN/m^2, 1203.5 – 524.7 kN/m^2 and 1458.6 – 631.8 kN/m^2 respectively. This trend of reduction in CBR and UCS at 7 days curing period for the strengthened soil as time limits for compaction after mixing increased was in agreement with [16, 17]. The CBR and UCS are measuring indices for the judging the strength ability of the strengthened soil. Steady decline in strength properties could be linked also to the level of compaction attained with a given compaction effort. As the time limits for compaction after mixing was increased, it resulted in lower level of compaction attained which consequently decreased the strength properties. The greater part of the strength properties achieved during the delay in compaction was necessarily by gaining strength through the process of hydration reaction.

3.4 Development of Models

The multiple regression models were of the polynomial form for cement and lime treated soil as shown in Equation (1) and (2) respectively. The dependent variable for the two equations was taken to be the time limits for compaction after mixing whereas OMC, cement content or lime content, CBR and UCS at 7 days curing period remain the independent variables in the models. In application, monitoring or predicting maximum permissible time limits for compaction after mixing would be possible using the models at a particular mix, compaction and strength properties during construction of road pavements in the field without rigorous laboratory experiments.

$$E = 412.256 - 0.005C^4 - 0.075M^3 + 0.016R^2 - 0.185S \quad (1)$$

$$E = 426.351 - 0.004L^4 - 0.092M^3 - 0.018R^2 - 0.111S \quad (2)$$

Table 2 Properties of Model from SPSS Worksheet for Equation 1

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
	0.988[a]	0.976	0.972	10.11260

a. Predictors; (Constant), C^4, M^3, R^2, S
b. Dependent Variable: E

Table 3 Coefficients of Predictors from SPSS Worksheet for Equation 1

Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig	95% Confidence Interval for B	
	B	Std. Error	Beta			Lower bound	Upper bound
Constant	412.256	11.394		36.182	.000	388.986	436.526
C^4	-.005	.001	-.315	-6.512	.000	-.007	-.003
M^3	-.075	.004	-.864	-20.145	.000	-.083	-.068
R^2	.016	.009	.210	1.831	.077	-.002	.034
S	-.185	.022	-.878	-8.272	.000	-.230	-.139

Table 4 Results of ANOVA from SPSS Worksheet for Equation 1

Model	Sum of squares	df	Mean Square	F	Sig.
Regression	122932.059	4	30733.015	300.524	.000[b]
Residual	3067.941	30	102.265		
Total	126000.000	34			

Table 5 Properties of Model from SPSS Worksheet for Equation 2

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.966[a]	0.933	0.924	16.75127

a. Predictors; (Constant), L^4, M^3, R^2, S
b. Dependent Variable: E

Table 6 Coefficients of Predictors from SPSS Worksheet for Equation 2

Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig	95% Confidence Interval for B	
	B	Std. Error	Beta			Lower bound	Upper bound
Constant	426.361	22.025		19.358	.000	381.371	471.332
C^4	-.004	.001	-.243	-3.579	.001	-.006	-.002
M^3	-.092	.008	-.944	-11.136	.000	-.109	-.075
R^2	-.018	.012	-.271	-1.439	.061	-.043	.008
S	-.111	.033	-.590	-3.361	.002	-.179	-.044

Table 7 Results of from SPSS Worksheet for Equation 2

Model	Sum of squares	df	Mean Square	F	Sig.
Regression	117581.853	4	29395.463	104.757	.000[b]
Residual	8418.147	30	280.605		
Total	126000.000	34			

Table 2 and 5 respectively show the summary of the models' properties for Equation 1 and 2. Coefficients of correlation denoted as 'R' value is a criterion for judging the accuracy of models' prediction. For Equation 1 and 2 respectively, 0.988 and 0.966 were the 'R' values. The 'R' value for any model with highest level of accuracy of predictions is 1. Therefore the models appeared to be very dependable for predicting '*E*' time limits for compaction after mixing. Coefficient of determination is referred to as 'R Square' which is a measure of the part of the variability that existed in the predicted variable which the predictors can explain. Equation 1 and 2 had 0.976 and 0.933 respectively as 'R Square' values. In other words, the 97.6% and 93.3% of the variability that existed in the prediction of the time limits for compaction after mixing for the cement or lime strengthened soil could be accounted for by the equations' constants, OMC, cement/lime contents of the strengthened lateritic soil as applicable by CBR and UCS at 7 days curing. It would appear that the polynomial model showed higher level of accuracy in prediction than the geometric model presented by [21] because the later had lower values of 0.902 and 0.814 as coefficients of correlation and coefficient of determination respectively.

The coefficients of the predictors in the polynomial models in Equation 1 and 2 are presented in Table 3 and 6 respectively. Table 3 also showed that the level of significance of OMC, cement content, CBR and UCS at7 days curing for Equation 1 were 0.000, 0.000, 0.077 and 0.000 respectively at 95% confidence level. Whereas in Table 6 for Equation 2, the level of significance for OMC, lime content, CBR and UCS at 7 days curing were 0.001, 0.000, 0.061 and 0.002 respectively at also 95% confidence level. These indicated that in predicting the time limits for compaction after mixing, the OMC, cement/lime contents as applicable, CBR and UCS at 7 days curing were all very statistically significant. This was because all the variables had values that were by far lower than 0.5, thus very high level of significance for all the variables. Therefore, a slight alteration of any of the variables would greatly influence the predicted value of the time limits for compaction after mixing.

The ANOVA results for Equation 1 and 2 were presented in Table 4 and 7 respectively. The overall polynomial models were of good fit for the data because the values of F-ratio for Equation 1 and 2 were 300.524 and 104.757 respectively.

4.0 CONCLUSION

Polynomial models were successfully developed for predicting the time limits for compaction after mixing operation for lateritic soil prepared with cement or lime in this study. The cement/lime content, compaction and strength characteristics were used as predictor variables. The followings were the findings after the study:

i. The untreated lateritic soil was grouped to share the same engineering behavior with A-6(13) soils in the AASHTO soil classification system and clayey soil (CL) in the Unified Soil Classification system.

ii. The lateritic soil was found to be a poor construction soil in its natural state which required to be strengthened with cement or lime for it to be useful for road pavements.

iii. When the lateritic soil was strengthened with cement or lime, compaction and strength characteristics all showed a reduction trend with a progressive rise in time limits for compaction after mixing.

iv. Polynomial models developed were a good fit for predicting time limits for compaction after mixing using the cement/lime contents, compaction and strength characteristics of the strengthened soil. The coefficients of correlation and determination gave values of 0.988 and 0.976, respectively, for cement-stabilized soil. Likewise, the lime-stabilized soil gave values of 0.966 and 0.933, respectively.

v. Cement/lime contents, OMC, CBR and UCS at 7 days of curing were entirely statistically significant in predicting time limits for compaction after mixing at a 95% confidence level.

Conflicts of Interest

The corresponding author confirms that all the authors approved the final state of the article. This article originated from the authors and there is no conflict of interest for this paper. All the results and findings presented in this study, especially the Figures are included as supplementary information file attachments. All other relevant materials or information like tables and charts that were referred to in this manuscript that supports the findings of this study can be supplied by the corresponding author if requested without any restriction because they are conventional standards for soil tests and characterization.

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