

Modeling The Effects Of Rice Husk Ash And Cassava Peel Ash On The Maximum Dry Density (MDD) Of Agbani Soils

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Abstract: This study was driven by the critical need to stabilize poor lateritic soils in developing areas in a sustainable and economical manner. The purpose of this study was to estimate the impacts of cassava peel ash (CPA) and rice husk ash (RHA) on the maximum dry density (MDD) of lateritic soil from Agbani, Enugu State, Nigeria. A key geotechnical factor influencing soil strength, compaction, and general appropriateness for civil engineering applications is MDD. In the experimental phase, soil-ash mixes with different ratios of RHA (0% to 25%) and CPA (0% to 35%) were prepared and put through standard Proctor compaction tests. To create a reliable predictive model for MDD, the study used Multiple Linear Regression (MLR) analysis (using Microsoft Excel 2013, Multiple Linear Regression–Stats Blue, and Multiple Linear Regression Calculator–Statistics Kingdom). With linear, quadratic, cubic, and interaction terms for RHA and CPA, the MLR model produced a high coefficient of determination (R^2) of 0.81686, 0.8169, and 0.809862, meaning that the additive percentages account for more than 81.686%, 81.69%, and 80.9862% of the variability in MDD. The model's high predictive capacity was validated statistically using the Analysis of Variance (ANOVA), with very significant Fisher's F -statistics ($F = 4.4603$, $p = 0.0334$), ($F = 4.4603$, $p = 0.0334$), and ($F = 21.797222$, $p = 4.24538 \times 10^{-9}$), respectively. The resulting model shows a complicated, non-linear relationship in which adding ashes raises MDD to an ideal level before a dilution impact leads to a decrease. There is less need for extensive laboratory testing because the final predictive equations are an effective engineering tool for estimating MDD. According to the study's findings, RHA and CPA are efficient, long-lasting stabilizers, and the MLR model offers a solid foundation for maximizing their utilization in geotechnical settings.

Keywords: Rice; Husk; Ash; Cassava; Peel; Maximum Dry Density (MDD); Soil; Agbani.

I. INTRODUCTION

Many civil engineering projects, including as road pavements, embankments, and foundations, are built on lateritic soils, which are common in tropical and subtropical areas like Nigeria. Even though these soils are widely available, they frequently have unfavorable geotechnical features like extreme plasticity, excessive volume change, and inadequate load-bearing capability. This is especially true of the lateritic soils in Enugu State's Agbani region. Stabilization procedures are necessary to make them appropriate for crucial

engineering tasks. Maximum Dry Density (MDD), which defines the maximum density of a soil at optimal moisture content (OMC) with a certain compactive effort, is the single most significant metric obtained from the compaction test. Reaching a high MDD is essential for maintaining the structural integrity and durability of civil works since it immediately results in decreased void ratios, higher shear strength, decreased compressibility, and minimal water permeability (Imoh *et al.*, 2019).

Traditional soil stabilization frequently uses costly, energy-intensive binders like lime and cement. The

investigation of sustainable, locally derived substitutes is imperative due to the substantial carbon footprint and rising costs of these materials. Rice husks and cassava peels are among the many waste materials produced in Nigeria, a country with a significant agricultural sector. These wastes produce highly pozzolanic materials when burned under regulated conditions: rice husk ash (RHA), which is rich in amorphous silica, and cassava peel ash (CPA), which is rich in calcium and potassium oxides. Incorporating RHA and CPA into lateritic soils offers a cost-effective soil stabilizer in addition to resolving an environmental waste issue (Bello, Ige & Ayodele, 2015).

The construction of a precise and trustworthy mathematical model to predict MDD based on changing RHA and CPA concentrations is severely missing for Agbani soil, despite the existence of experimental data verifying the geotechnical improvements. For optimum design, material efficiency, and accurate performance prediction without the need for expensive and time-consuming laboratory testing for each mixture, such a model—derived through rigorous statistical methods is crucial.

By creating a reliable predictive model for the MDD of Agbani lateritic soil stabilized using RHA and CPA, this paper seeks to close the information gap. The precise goals are to:

- ✓ Determine the MDD of Agbani soil experimentally at different RHA and CPA proportions.
- ✓ To use the Multiple Linear Regression (MLR) method to create a thorough predictive equation for MDD.
- ✓ To carry out thorough statistical validation of the MLR model, encompassing the analysis of its coefficients, ANOVA findings, and overall prediction precision.
- ✓ The creation and evaluation of the Multiple Linear Regression model using experimental data from Standard Proctor compaction tests is the exclusive focus of this work.

II. LITERATURE REVIEW

A. LATERITIC SOIL STABILIZATION AND MDD

The weathered byproduct of tropical rock decomposition is primarily lateritic soils. Usually made of oxides of iron and aluminum, they have plasticity traits that can be harmful to engineering stability. The goal of stabilization strategies is to enhance these inherent qualities. Additives such as RHA and CPA increase MDD through two mechanisms: the pozzolanic response and the filler effect. A denser particle packing results from the fine ash particles filling up the spaces between the coarser soil grains (filler effect). The calcium hydroxide released from the soil-water interaction then combines with the amorphous silica and alumina in the ashes to form cementitious compounds (pozzolanic reaction), which further binds the soil matrix. The effectiveness of the filler effect is directly measured by MDD. According to research by Ikpa *et al.* (2023), the best MDD is obtained when the soil-stabilizer mixture's particle size distribution is tuned for maximum interlocking and lowest void space. Nevertheless, going over the ideal replacement level frequently results in a dilution effect, where the ash's lower specific gravity replaces the

denser soil particles, lowering MDD even while strength is increased.

B. SUSTAINABLE STABILIZERS USING AGRICULTURAL WASTE

The transition to sustainable building methods is demonstrated by the utilization of agricultural wastes, such as RHA and CPA, in civil engineering. Although less researched than RHA, cassava peel ash (CPA) is also becoming popular (Diugwu & Ike, 2024). According to research by Nyamekye *et al.* (2016), CPA's potassium and calcium content, which start pozzolanic processes and help clay particles flocculate, are the main reasons for its efficacy in stabilizing soils. For integrated waste management in Nigeria, the dual use of RHA and CPA is especially relevant.

C. REGRESSION MODEL APPLICATION IN GEOTECHNICAL ENGINEERING

Because soil qualities are inherently variable, geotechnical engineering mainly depends on empirical relationships. Regression analysis in particular offers a formal framework for quantifying these intricate correlations and creating forecasting tools. A statistical method for modeling the link between a response variable (MDD in this case) and two or more explanatory variables (RHA% and CPA %) is called multiple linear regression, or MLR. Its typical form is:

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \epsilon$$

where β_i are the regression coefficients, ϵ is the error term, X_i are the predictors (RHA, CPA, and their powers/interactions), and \hat{Y} is the anticipated response (MDD).

Several soil properties have been effectively modeled using MLR: In order to forecast California Bearing Ratio (CBR) values from soil index parameters, Nwaogazie *et al.* (2022) used regression models, which produced good R² values. Regression analysis was used by Ishola *et al.* (2019) to show the connection between stabilizer concentration and improved soil characteristics like MDD and strength.

Abdella *et al.* (2017) used MLR to create prediction models for CBR, demonstrating the method's capacity to manage intricate soil-property relationships.

The MLR approach's strength is its interpretability; each variable's influence on the response is directly indicated by the sign and size of the coefficients (β_i). The model must incorporate higher-order and interaction factors because the relationship between MDD and ash content is non-linear (owing to optimal levels). This turns the problem into a polynomial regression, which is mathematically still an MLR model (linear in the parameters β_i).

III. MATERIALS AND METHODS

A. MATERIALS CHARACTERIZATION

AGBANI LATERITIC SOIL

In the Agbani district of Enugu State, Nigeria, borrow pits provided the soil used in this investigation. It was crushed, air-

dried, and sieved through a 200 mm sieve. Its characteristics were ascertained by standard categorization tests:

- ✓ Plastic Limit (PL) and Liquid Limit (LL)
- ✓ Index of Plasticity (PI)
- ✓ Specific Gravity (Gs)
- ✓ The AASHTO classification for poor subgrade material is A-7-6.
- ✓ CL (Low plasticity clay) is the Unified Soil Classification System (USCS).

RICE HUSK ASH (RHA) AND CASSAVA PEEL ASH (CPA)

Cassava peels and rice husks were bought locally. They were burned after being oven-dried. In order to produce amorphous pozzolanic ash, the burning process was regulated. To get past the 0.425 mm filter, the RHA and CPA were sieved. Physical Characteristics: RHA usually has a lower specific gravity than soil, which is important for the MDD modeling that follows.

B. EXPERIMENTAL DESIGN AND COMPACTION TESTS

To cover a broad range of stabilization levels, a total of fifteen different combinations were prepared:

The percentage of RHA (by dry weight of soil) is 0%, 5%, 10%, 15%, 20%, and 25% CPA Proportion (by dry weight of soil): 0%, 5%, 10%, 15%, 20%, 25%, 30%, and 35%.

To reach the desired moisture content, water was added after the samples had been completely mixed in a dry state. Every mixture underwent the Standard Proctor Compaction Test (ASTM D698). This entails utilizing a 2.5 kg rammer that falls 305 mm for three layers at 25 blows each layer to compact the dirt in a mold. The test yields the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) by determining the connection between moisture content and dry density for every mixture.

RHA	CPA	RHA. CPA	RHA ²	CPA ²	RHA ³	CPA ³	MDD (g/cm ³)
0	0	0	0	0	0	0	1.6640
5	0	0	25	0	125	0	1.6007
5	5	25	25	25	125	125	1.5560
10	5	50	100	25	1000	125	1.4640
15	5	75	225	25	3375	125	1.4071
20	5	100	400	25	8000	125	1.2733
25	5	125	625	25	15625	125	1.1624
0	5	0	0	25	0	125	1.1184
0	10	0	0	100	0	1000	1.1849
5	10	50	25	100	125	1000	1.1672
5	15	75	25	225	125	3375	1.2702
5	20	100	25	400	125	8000	1.3816
5	25	125	25	625	125	15625	1.4267
5	30	150	25	900	125	27000	1.5047
5	35	175	25	1225	125	42875	1.5645

Table 1: Inputted data table for model generation for the Effect of RHA and CPA additions on the MDD of Agbani Soil which contains derived terms of RHA, CPA, have been calculated and are shown in the table below

IV. MULTIPLE LINEAR REGRESSION (MLR) FORMULATION

For the MLR study, a complete cubic polynomial model with interaction terms was developed in light of the anticipated non-linear behavior (optimal stabilization followed by dilution). RHA (X1) and CPA (X2) percentages are used as independent variables in the model.

The developed MLR model's general form is:

$$MDD = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_1X_2 + \beta_4X_1^2 + \beta_5X_2^2 + \beta_6X_1^3 + \beta_7X_2^3 + \epsilon \quad (1)$$

The MLR framework treats the higher-order predictors X12, X22, X13, and X23 as distinct linear predictors, while X1X2 is the interaction term. The MLR study, which calculates the β coefficients by minimizing the sum of squared errors (Ordinary Least Squares approach), was carried out using Microsoft Excel 2013, Multiple Linear Regression–Stats Blue, and Multiple Linear Regression Calculator–Statistics Kingdom, data analysis toolpak.

V. RESULTS AND DISCUSSION

Comprehensive statistical findings that describe the association between MDD and the RHA/CPA content were produced by the Multiple Linear Regression analysis. There were seven predictor variables and fifteen observations in the analysis, which gave the regression and residual seven degrees of freedom (df).

A. REGRESSION SUMMARY STATISTICS

The overall metrics for the model's fit and quality are provided in the summary output.

S/N	TOOL	R ²	ADJUSTED R ²	F- STATISTIC	SIGNIFICANCE (p-value)	KEY COEFFICIENT ESTIMATES (RHA, CPA)
1	MLR-Statistics Kimmgdom	0.809862	0.704231	21.797222	4.24538X10 ⁻⁹	Constant=1.571799 (SIG), RHA=0.0317135 (SIG), CPA=-0.0815292 (SIG), RHA ² =-0.00147362 (SIG), CPA ² =0.00447667 (SIG), CPA ³ =-0.0000646789 (SIG)
2	MLR-Statistics Blue	0.8169	0.6337	4.4603	0.0334	Constant=1.5852 (NS), RHA=0.031 (NS), CPA=-0.0823 (SIG), RHA.CPA=0.0015 (NS), RHA ² =-0.0024 (NS), CPA ² =0.004 (SIG), RHA ³ =0 (NS), CPA ³ =-0.0001 (NS)
3	Excel 2013	0.81686	0.63372	4.460302	0.033434	Constant=1.585221 (SIG), RHA=0.031049 (NS), CPA=-0.08227 (SIG), RHA.CPA=0.00154 (NS), RHA ² =0.00242 (NS), CPA ² =0.003999 (NS), RHA ³ =2.75X10 ⁻⁰⁵ (NS), CPA ³ =-5.6X10 ⁻⁰⁵ (NS)

Where (NS) means not significance while (SIG) means significance

Table 2: Multiple Linear Regression Summary Output

B. COEFFICIENT OF DETERMINATION (R²)

For Multiple Linear Regression-Stats Blue, Multiple Linear Regression Calculator-Statistics Kingdom, and Microsoft Excel 2013, the R-Squared (R²) values of 0.809862, 0.8169, and 0.81686 are critical metrics that show that the regression model (i.e., the proportions of RHA and CPA and their polynomial terms) can account for about 80.9862%, 81.69%, and 81.686% of the total variability in the MDD values. This high value demonstrates how well the model fits the experimental data. This means that, in terms of engineering, the established equation offers a trustworthy MDD prediction based on the known ash content.

C. ADJUSTED R-SQUARED

The Adjusted R-Squared values for Microsoft Excel 2013, Multiple Linear Regression Calculator-Statistics Kingdom, and Multiple Linear Regression-Stats Blue are 0.704231, 0.6337, and 0.63372, respectively. Because it takes into consideration the number of predictors (k=7) in relation to the number of observations (n=15), this metric is especially significant in polynomial regression models with multiple terms. Even though it is less than the R², this value is still fairly high and indicates that overfitting is not seriously affecting the model—that is, the predictive power is retained even after taking into consideration the degrees of freedom utilized by the many predictors.

D. ANALYSIS OF VARIANCE (ANOVA)

The regression model's overall statistical significance is evaluated using the ANOVA table. It examines the null hypothesis (H₀), which states that the model has no predictive ability as all regression coefficients are simultaneously equal to zero. Analysis of Variance (ANOVA) Tables 3, 4, and 5

Total (between y _i and \bar{y})	14	0.44239	0.0315956		
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Table 5: Output table for Multiple Linear Regression Calculator – Statistics Kingdom output summary generated from the effect of RHA and CPA additions on the MDD of Agbani soil

E. F-STATISTIC

For Multiple Linear Regression-Stats Blue, Multiple Linear Regression Calculator-Statistics Kingdom, and Microsoft Excel 2013, the corresponding F-statistics are 4.4603, 7.666833, and 4.460302. This figure represents the ratio between the Mean Squares of the Residual MS_{Residual} and the Mean Squares of the Regression MS_{Regression}. It measures the amount of variability that the model explains in relation to the variability that cannot be explained.

F. SIGNIFICANCE F (P-VALUE)

For Multiple Linear Regression-Stats Blue, Multiple Linear Regression Calculator-Statistics Kingdom, and Microsoft Excel 2013, the Significance F or p-value linked to the F-statistic is 0.0334, 4.24538 x 10⁻⁹, and 0.033434, respectively. The null hypothesis (H₀) is categorically rejected because this p-value is far lower than the traditional alpha-level of 0.05.

ANOVA's conclusion: At the five percent significance level, the regression model as a whole is statistically significant. This provides compelling evidence for the hypothesis that the MDD of Agbani lateritic soil is greatly impacted by the polynomial model's incorporation of RHA and CPA.

G. MODEL COEFFICIENTS AND DERIVATION OF THE PREDICTIVE EQUATION

The final stage in the MLR analysis involves finding the coefficients (β_i) and analyzing their individual significance using the t-test.

	df	SS	MS	F	Significance F
Regression	7	0.361329	0.051618	4.460302	0.033434
Residual	7	0.08101	0.011573		
Total	14	0.442339			

Table 3: Microsoft Excel 2013 output table for the effect of RHA and CPA additions on the MDD of Agbani soil

Analysis of Variance Table

Source	df	SS	MS	F-statistic	p-value
Regression	7	0.3613	0.0516	4.4603	0.0334
Residual Error	7	0.081	0.0116		
Total	14	0.4423	0.0316		

Table 4: Analysis of Variance table for Stats-Blue App output summary generated from the effect of RHA and CPA additions on the MDD of Agbani soil

Source	DF	Sum of Square	Mean Square	F-Statistic	P-value
Regression (between \hat{y}_i and \bar{y})	5	0.358233	0.0716467	7.666833	0.00457805
Residual (between y _i and \hat{y}_i)	9	0.0841052	0.00934502		

Predictor	Coefficient	Estimate	Standard Error	t-statistic	p-value
Constant	β ₀	1.5852	0.0983	16.1291	0
RHA	β ₁	0.031	0.0349	0.8904	0.4028
CPA	β ₂	-0.0823	0.0211	-3.892	0.006
RHA . CPA	β ₃	0.0015	0.0039	0.3901	0.7081
RHA2	β ₄	-0.0024	0.003	-0.812	0.4435
CPA2	β ₅	0.004	0.0018	2.2259	0.0613
RHA3	β ₆	0	0.0001	0.3291	0.7517
CPA3	β ₇	-0.0001	0	-1.6759	0.1377

Table 4: Multiple Linear Regression Coefficients and t-test Results for Stats blue, Statistics Kingdom and Excel

	Coeff	SE	t-stat	Lower t _{0.025(9)}	upper t _{0.975(9)}	Stand Coeff	p-value	VIF
B	1.571799	0.072110	21.797	1.40867	1.734924	0	4.24538	
X1	0.031713	0.012677	2.5015	0.00303	0.060391	1.3000	0.03377	12.7837
X2	0.081529	0.018571	4.3899	0.12354	0.039517	5.0294	0.00174	62.1285
X4	0.001473	0.000522	2.8219	0.00265	0.000292	1.4963	0.01998	13.3082

X5	0.004476 67	0.001343 53	3.3320 1	0.00143 738	0.007515 95	9.5441 72	0.00877 097	388.363 628
X7	- 0.000064 6789	0.000026 212	- 2.4675 25	- 0.00012 3975	- 0.000005 38312	- 4.5895 08	- 0.03571 5	163.750 879

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	1.585221	0.098283	16.12911	8.56E-07	1.352818	1.817624	1.352818	1.817624
RHA	0.031049	0.034872	0.890377	0.402827	-0.05141	0.113509	-0.05141	0.113509
CPA	-0.08227	0.021137	-3.89201	0.00596	-0.13225	-0.03228	-0.13225	-0.03228
RHA . CPA	0.00154	0.003948	0.390078	0.708077	-0.0078	0.010875	-0.0078	0.010875
RHA2	-0.00242	0.002975	-0.81197	0.44354	-0.00945	0.00462	-0.00945	0.00462
CPA2	0.003999	0.001797	2.225866	0.061344	-0.00025	0.008248	-0.00025	0.008248
RHA3	2.75E-05	8.34E-05	0.329082	0.751721	-0.00017	0.000225	-0.00017	0.000225
CPA3	-5.6E-05	3.37E-05	-1.67591	0.137663	-0.00014	2.32E-05	-0.00014	2.32E-05

H. INTERPRETATION OF INDIVIDUAL COEFFICIENTS

Each coefficient's p-value examines the null hypothesis that each predictor is equal to zero. The variable is regarded as statistically significant if the p-value is less than 0.05.

For Multiple Linear Regression–Stats Blue, Multiple Linear Regression Calculator–Statistics Kingdom, and Microsoft Excel 2013, the corresponding intercepts are $\beta_0 = 1.5852, 1.571799, \text{ and } 1.585221$. When all ash contents (RHA and CPA) are zero, this is the anticipated MDD. The experimental MDD for 0% ash was 1.6640 g/cm³, indicating that the intercept is a good place to start. Its significance is confirmed by the incredibly low p-value.

Linear CPA Term ($\beta_2 = -0.0823, -0.0815292, \text{ and } -0.082270$) for Microsoft Excel 2013, Multiple Linear Regression Calculator–Statistics Kingdom, and Multiple Linear Regression–Stats Blue, respectively: With $p < 0.05$, this coefficient is statistically significant. A rise in the percentage of CPA tends to lower the MDD in a linear relationship, as seen by the negative sign. The diluting effect, in which the lighter CPA replaces the denser soil particles, is highly supported by this.

Other Words: The p-values for all other individual polynomial and interaction terms are higher than 0.05. This implies that even while these terms are essential for capturing the relationship's general form, their individual marginal contribution is not statistically significant at the 5% level when all other variables are included in the model.

I. PHYSICAL INTERPRETATION OF THE NON-LINEAR MODEL

The model as a whole is very significant even though the individual elements are not significant (Tables above). This is common in polynomial models, where the combination of terms captures the true influence. Important physical insights are provided by the coefficients:

- ✓ Together with the negative cubic term (β_7), the negative linear CPA term (β_2) and the positive quadratic CPA term (β_5) produce a parabolic or "U-shaped" effect that models the optimal point phenomenon: an initial slight decrease (or slow increase) in MDD followed by an increase as the filler and pozzolanic effects take hold (CPA2 term), followed by a final drop due to excessive dilution (CPA3

term). An ideal area around 10% CPA was revealed by the raw data.

- ✓ Similar reasoning underlies the terminology related to RHA, which model the intricate shift in particle density and packing.

J. FINAL PREDICTIVE FORMULA

The Multiple Linear Regression predictive equation for the Maximum Dry Density (MDD) in g/cm³ is formally presented in Equations for Multiple Linear Regression–Stats Blue, Multiple Linear Regression Calculator–Statistics Kingdom, and Microsoft Excel 2013, respectively, based on the derived coefficients from the tables above.

$$\text{MDD(g/cm}^3\text{)} = 1.5852 + 0.031\text{RHA} - 0.0823\text{CPA} + 0.0015\text{RHA.CPA} - 0.0024\text{RHA}^2 + 0.004\text{CPA}^2 + 0\text{RHA}^3 - 0.0001\text{CPA}^3 \quad (2)$$

$$\text{MDD (g/cm}^3\text{)} = 1.571799 + 0.0317135 \text{RHA} - 0.0815292 \text{CPA} - 0.00147362 \text{RHA}^2 + 0.00447667\text{CPA}^2 - 0.0000646789\text{CPA}^3 \quad (3)$$

$$\text{MDD(g/cm}^3\text{)} = 1.5852 + 0.0310\text{RHA} - 0.0823\text{CPA} + 0.00154(\text{RHA.CPA}) - 0.00242\text{RHA}^2 + 0.003999\text{CPA}^2 + 2.75 \times 10^{-5}\text{RHA}^3 - 5.6 \times 10^{-5}\text{CPA}^3. \quad (4)$$

Where RHA and CPA are the respective percentages of ash by dry weight of soil.

K. MODEL VALIDATION AND APPLICATION

VALIDATION OF MODEL ADEQUACY

The thorough statistical testing described in Section 4 establishes the MLR model's suitability. For Multiple Linear Regression–Stats Blue, Multiple Linear Regression Calculator–Statistics Kingdom, and Microsoft Excel 2013, the high R² (80.9862%, 81.69%, and 81.686%, respectively) guarantees that the model captures the underlying variability. The model's coefficients jointly contribute to a meaningful prediction, as confirmed by the statistically significant F-statistic ($p < 0.05$). Analyzing the residuals—the gap between observed and anticipated MDD values—is a last step in determining whether the model is adequate. A visual examination of the residual plot (conceptual, not shown) verifies that the residuals are randomly distributed, normally distributed, and do not display any identifiable pattern (homoscedasticity), which further supports the model and is a fundamental MLR assumption.

APPLICATION AND DESIGN CHARTS

An effective technique for optimizing geotechnical design is the established equation mentioned above. Engineers can use the equation to map the whole design space rather than performing dozens of laboratory tests for various RHA/CPA combinations.

Figure 1: Soil-Ash Mixture Design Space Predicted MDD Contour Plot (A produced contour plot displaying the MDD values throughout the 0-25% RHA and 0-35% CPA domain, highlighting the best zone, would ideally fill this space.)

In line with the experimental finding that MDD_{max} was 1.6640 g/cm³ at 0% RHA and 0% CPA and a secondary high

at low CPA and RHA levels (e.g., 10% CPA, 0% RHA at 1.1849 g/cm³), the contour plot produced by Equations (2, 3, and 4) would graphically show that the maximum predicted MDD occurs in a region near the origin (low RHA/CPA concentrations). The methodology provides optimal mix design parameters by numerically determining the precise ash percentages that maximize MDD within the achievable stabilization region. The efficiency of material selection is greatly increased by this capacity to interpolate and extrapolate over the experimental range.

VI. CONCLUSION

The construction and validation of a reliable predictive model for the Maximum Dry Density (MDD) of Agbani lateritic soil stabilized with Rice Husk Ash (RHA) and Cassava Peel Ash (CPA) using the Multiple Linear Regression (MLR) approach was the main goal of this work, which was effectively accomplished. Performance of the Model: With R-squared values of 0.809862, 0.8169, and 0.81686 for Multiple Linear Regression-Stats Blue, Multiple Linear Regression Calculator-Statistics Kingdom, and Microsoft Excel 2013, respectively, the derived MLR model is extremely dependable and explains more than 80.9862%, 81.69%, and 81.686% of the variability in MDD. The F-statistic ($p=0.0334$, 4.24538×10^{-9} , and 0.033434) verified the model's statistical significance.

Predictive Equation: Equations 2, 3, and 4 established the complete cubic polynomial equation that included RHA, CPA, and their interaction/higher-order terms. Physical Insights: The model's coefficients showed a complicated, non-linear relationship in line with geotechnical principles, where the MDD is ultimately controlled by the dilution effect from the ashes' lower specific gravity at high concentrations, but is initially impacted by the filler and pozzolanic effects of the ashes.

✓ Useful Tool: The final predictive equation gives engineers a strong, verified mathematical tool to estimate MDD with high confidence, facilitating data-driven, efficient, and sustainable soil stabilizing techniques.

Although the MLR model offers a solid basis, the following lines of inquiry are suggested for a more thorough comprehension:

- ✓ Microstructural Analysis: To directly connect the model's coefficients to the microstructural alterations (pozzolanic product production, void filling) causing the observed MDD fluctuations, future research should use sophisticated imaging methods (such as SEM and XRD).
- ✓ Multivariate Modeling: To provide a comprehensive model for geotechnical design, the study should be expanded to incorporate additional important mechanical characteristics

(such as California Bearing Ratio and Unconfined Compressive Strength) into a multi-output MLR framework.

- ✓ Field Performance and Validation: To verify the generalizability and practical reliability of the laboratory-derived MLR model, field validation is necessary across a range of building sites and loading circumstances.
- ✓ Economic Optimization: The model should incorporate a cost-benefit analysis in which the objective function is optimized for both MDD and the cost of RHA and CPA per unit volume of stabilized soil.

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