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Research Article

Predicting the strength properties of clay soil stabilized with wheat husk ash and lime

Adesoji Amos Adekanle [1,a], Emmanuel Akintunde Okunade [1,b], Benjamin Ayowole Alo [1,c], Temitope Funmilayo Awolusi [2,d], Marc Azab [*,3,e]

[1]*Department of Civil Engineering, Ekiti State University, Ado Ekiti, Ekiti State, Nigeria*
[2]*Department of Civil Engineering, Bamidele Olumilua University of Education, Science and Technology, Ikere - Ekiti, Ekiti State, Nigeria*
[3]*College of Engineering and Technology, American University of the Middle East, Egaila 54200, Kuwait*

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Abstract

The geotechnical qualities of the soil influence the stability of civil engineering structures. Although clay soil is a varied and challenging material, it is widely utilized in construction due to its availability and low cost. The stabilization of clay soil by incorporating lime and wheat husk ash provides an avenue to improve the behavior of clay soil and also promote environmental sustainability in road construction. The study considered different combinations of lime and wheat husk ash, varying between 0% and 8%, and measured the weight of the dry soil at all percentages. The maximum dry density, consistency limit, California bearing ratio, unconfined compressive strength, and erodibility potential of the stabilized soil were evaluated to assess its performance. The prediction of soil properties using the response surface methodology approach is a novel contribution in this paper. This study uniquely integrates wheat husk ash and lime for prediction modeling of soil properties with good accuracy, as indicated by the coefficient of determination of 0.91, 0.87, 0.86, 0.77, and 0.95 for the maximum dry density, soaked California bearing ratio, unsoaked California bearing ratio, unconfined compressive strength, and erodibility potential, respectively. In addition, the trend of the experimental data was evaluated by visualization using the 2D contour plots of RSM. The plots indicated an optimum content of 2% for WHA and a lime content between 6% and 8% for improved soil performance. Analysis of variance was performed on the experimental data to identify significant terms, and predictive models were validated, with the majority of the experimental data falling close to the model predictions.

1. Introduction

Agricultural wastes refer to the remnants obtained from the cultivation and processing of agricultural products, including crops, vegetables, fruits, poultry, dairy products, and meat. Obi et al.[1] also refers to agricultural wastes as non-product outputs of agricultural production and processing, which contain materials that may be beneficial to humans but whose economic values are less than the collection, transportation, and processing costs. Increased agricultural production is inevitable due to the continuous growth in the global human population. Agricultural production is believed to have increased more than threefold in the last five decades. Other factors that have contributed to increased agricultural productivity include technological advancements associated

*Corresponding author: marc.azab@aum.edu.kw
[a]orcid.org/0009-0009-2010-3481; [b]orcid.org/0000-0002-1160-5983; [c]orcid.org/0009-0000-7698-7006; [d]orcid.org/0000-0002-6400-142x; [e]orcid.org/0000-0003-0173-3209
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with the Green Revolution and the expansion of agricultural land [2]. It is estimated that the agriculture sector produces around 24 million tons of food per year. Crop production is often accompanied by waste generation, which also poses health hazards and harms the ecosystem [3]. The wheat crop is one of the most extensively grown crops and ranks second in overall cereal crop production [4]. Hence, utilizing its waste component in construction can promote environmental sustainability. The wheat husk generated in the harvesting process is collected from agricultural areas and calcined at 600°C to produce fine ash residue. This ash contains a large amount of silica, which aids soil fertility [5].

Agro-waste ash is a potential alternative to lime, as agro-waste is produced in Nigeria in hundreds of thousands of metric tons annually. Due to the presence of calcium oxides, agro-waste ash can be used as a substitute for lime and cement, which are traditionally considered admixtures for soil stabilization. The use of agro-waste for soil stabilization will provide value to the agro-waste and also reduce the amount of environmental pollution caused by it [6]. Portland cement production process increases CO_2 emissions, which contributes to the melting of the ozone layer that covers the Earth's surface. As a result, substituting agricultural waste materials such as Rice Husk Ash (RHA), WHA, and others for soil stabilization will lessen the overall environmental impact of the stabilization process [7]. Kumar et al. [8] evaluated the use of wheat straw ash (WSA) as a partial cement replacement for enhancing the properties of high plastic clay. The test aims to assess various properties, including maximum dry density, optimum moisture content, California bearing ratio, and unconfined compressive strength. It was concluded that the incorporation of WSA reduces the cost of soil stabilization, the amount of waste to be disposed of in the environment, and replaces a portion of the cement needed to safeguard the environment. According to Pandey et al. [9], environmentally conscious practices in the construction field can be achieved through waste recycling. Recent studies by Khadaywi et al. [10] and Asyhai-Kgljahi et al. [11] have also explored the use of recycled waste for sustainable construction.

Previous efforts have been made to provide predictive models for soil stabilization using various parameters. Okonkwo et al. [12] have applied the exponential logarithm approach in predicting the strength properties of the soil using three input variables (cement content, rice husk ash, and optimum moisture content). This approach was able to predict only the California bearing ratio and the unconfined compressive strength at 7 days. Another study by Assam and Agunwamba [13] has also employed the Scheffe higher model to predict the California bearing ratio and the unconfined compressive strength, using oyster shell ash, water, and soil as input parameters. Previous studies have focused on predicting the California Bearing Ratio and the unconfined compressive strength of the soil using three parameters. However, the Response Surface Methodology (RSM) option, as a predictive tool, utilizes minimal input variables and experimental data. This study explored the potential of two input parameters for not only predicting the soil's California bearing ratio and the unconfined compressive strength, but also the maximum dry density and the erodibility potential of the stabilized soil. The varying percentage of lime and WHA was considered as input parameters in predicting the desired response. The RSM is a statistical tool that is effective for designing experiments, evaluating the effects of factors, model building, and attaining optimal experimental conditions [14-18]. In RSM, two or more factors that vary simultaneously can be fitted to a quadratic function [19]. It presents a better option for optimizing multiple input factors with a minimum number of experimental trials, serving as an alternative to the one-factor-at-a-time approach, which can be tedious and does not account for factor interactions [20]. RSM provides a mathematical model for predicting the desired properties [21]. It has been applied in various industries, including Engineering, Biotechnology, Marketing, and Advertising [22-24]. RSM considers the quadratic, interaction, and linear terms of input factors or parameters in relation to the desired response. It identifies variables that have significant contributions to the process and also investigates the relationship between the independent variables and the anticipated output(s) [25]. RSM employs up-to-date techniques for handling complex experimental designs, particularly when certain factors are significant in predicting the behavior of a system [26].

2. Materials and Methods

2.1 Sample Preparation

The disturbed sampling technique was employed for collecting soil samples from the Federal Polytechnic gate on Ado-Ikare Road, Ekiti State, Nigeria. (Latitude $7^0$36'10''N and longitude $5^0$18'10''E). The collected samples were stored in polythene bags to retain natural moisture content until testing time. The hydrated lime was sourced locally, pulverized, and sieved through a 300 μm mesh. Wheat husk was collected from a farm settlement in Kano State, Nigeria, and transported to Ado-Ekiti in sack bags. The calcination process was conducted under laboratory conditions at a controlled temperature of 600 °C for 2 hours using a temperature-regulated muffle furnace with a maximum capacity of 1200 °C. The ash obtained was then sieved through a 300 μm sieve.

2.2 Test Procedure

Preliminary tests, including specific gravity, sieve analysis, and Atterberg limits, were conducted on the soil samples in accordance with BS 1377: Part 2 [27]. The soil was classified as A-7-6 (156) according to the AASHTO Classification. It had a specific gravity of 2.12, with a gradation comprising 32.33% silt, 25.52% clay, 35.84% sand, and 6.3% gravel. The consistency of different combinations of lime and WHA was determined to assess the liquid limit and plastic limit of soil samples that passed through a 0.425 mm sieve. The mineral composition analysis was conducted at the National Steel Raw Material Exploration Agency in Kaduna, Nigeria. The major compounds in the soil include silica (SiO_2) at 53.799%, aluminum oxide (Al2O3) at 17.589%, and Ferric oxide (Fe2O3) at 17.531%. The soil's oxide composition showed that the ratio of silica to sesquioxides (Alumina + Ferric oxide) is indicative of laterite, as the value was within the range of 1.33 to 2.00. WHA was observed to contain 7.3% SiO_2, 4.6% Al_2O_3, and 2.2% Fe_2O_3, making a combined total of 14.1%, which suggests that it is not pozzolanic but can function as a supplementary stabilizing additive. The treated samples were prepared by thoroughly mixing the pulverized soil with the required amount of Lime and WHA. Ten different combinations were considered in the study, which are 0% lime + 0% WHA, 8% lime + 0% WHA, 7% lime + 1% WHA, 6% lime + 2% WHA, 5% lime + 3% WHA, 4% lime + 4% WHA, 3% lime + 5% WHA, 2% lime + 6% WHA, 1% lime + 7% WHA, and 0% lime + 8% WHA. The different combinations of stabilizing agents were incorporated as a percentage weight of the dry soil, and samples were prepared in triplicate.

The soil compaction test was conducted in three layers using the Standard Proctor mold, and each layer received 25 blows from a 2.5 kg rammer dropped from a height of 300 mm. The process was repeated until the weight of the soil was reduced, and the optimum moisture content (OMC) was taken as the moisture content at which the maximum dry density (MDD) is attained. The unconfined compressive strength was determined using specimens from the Proctor mould, applying a correction factor of 1.04 to ensure results conform to cylindrical specimens with a height-to-diameter ratio of 2:1 or 150 mm cube specimens, as stipulated by BSI 1924[28]. A desiccator was used to cure the specimen for 7 days, and testing was carried out in accordance with BS 1377: Part 2 [27]. The specimens for the California Bearing Ratio were prepared in five (5) layers, with each layer receiving 62 (Sixty-two) blows of the rammer and soaked for 24 hours. The load that is required for a circular 49.95 mm diameter penetration at a specified rate of 1.25 mm/min was measured and used to compute the CBR. The actual force values for each penetration, as displayed on the plunger, were expressed as a percentage of a standard force. The study considered penetration depths of 2.5 mm and 5.0 mm, caused by loads of 13.2 kN and 20 kN, respectively. The experimental results of the soil properties were analyzed after 7 days of curing for the specimens. Finally, the face-centered central composite design of RSM was used to analyze the experimental results, utilizing the aforementioned combinations to obtain predictive models.

3. Results and Discussion

3.1 Compaction characteristics

The results of the standard proctor test for maximum dry density (MDD) and Optimum Moisture Content (OMC) at different combinations of Lime and WHA mixed with the soil samples are presented in Table 1. The OMC values for combinations of 0:0, 8:1, 7:1, 6:2, 5:3, 4:4, 2:6, 1:7 and 0:8 was found to be 17.8%, 20.2%, 14.8%, 16.2%, 16.4%, 17.8%, 18.2%,16.9%, 13.7% and 18.5% respectively. This Table also presents the corresponding MDD of soil samples for the different combinations of Lime and WHA. It was observed that the MDD and their corresponding OMC followed no particular trend with the incorporation of different proportions of lime and WHA content. However, it was observed that there was a 0.34%, 2.4%, 3.39% and 1.2% increase in the MDD values for combinations of 8:1, 7:1, 6:2 and 5:3 respectively with reference to 0:0. The increase in MDD values may be attributed to effective void reduction in the soil samples due to the incorporation of certain amount of lime and WHA in the soil which has provided a more formidable hardening process. For the combinations of 4:4, 3:5, 2:6, 1:7, and 0:8, there was a shortfall in MDD values when compared to the reference sample. From this observation, it could be inferred that when combining Lime and WHA for soil stabilization, it is required that the lime content should be greater than that of the WHA content for improved MDD.

Table 1. Results of compaction characteristics

S/N	Lime: WHA	MDD (kg/m^3)	OMC (%)
1	0:0	1739	17.8
2	8:0	1745	20.2
3	7:1	1781	14.8
4	6:2	1798	16.2
5	5:3	1760	16.4
6	4:4	1720	17.8
7	3:5	1732	18.2
8	2:6	1662	16.9
9	1:7	1665	13.7
10	0:8	1603	18.5

3.2 Consistency Limits

The variation in consistency limits for the different combinations of lime: WHA is presented in Fig. 1. It was observed that the Liquid limit (LL) and Plastic Limit (PL) increased for all combinations of lime: WHA with reference to sample 0:0. From these results the following plasticity index (LL-PL) values of 25.34, 11.62, 11.65, 10.73, 11.64, 16.70, 20.93, 23.03 and 26.89 were computed for combinations 0:0, 8:0, 7:1, 6:2, 5:3, 4:4, 3:5, 2:6, 1:7 and 0:8 respectively. The stabilization process resulted in a reduced plasticity index value for all combinations, except for combination 8:0.

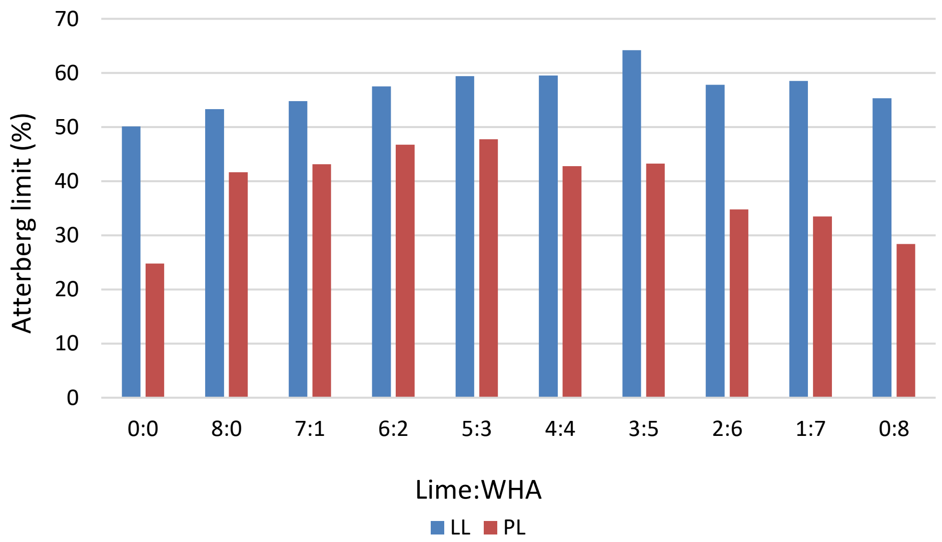


Fig. 1. Results of consistency limits

The lowest plasticity index value of 10.73 was observed for combination 6:2, indicating an improvement in the soil condition. The decrease in plasticity index value may be attributed to the ability of the stabilized soil sample to absorb more water in the presence of lime: WHA. The reduction in the PI is consistent with the findings of Gupta et al. [29]. This can be attributed to the hydration of the additives, particularly lime, which in turn produces a stiff soil mixture [30]. Also, this behavior may be a result of the colloidal reaction of the stabilizing agents. This substitutes the cations on the soil surface with calcium cations, resulting in the aggregation of colloidal soil particles, making them less plastic [31]. Other combinations, such as 8:0, 7:1, and 5:3, also had a plasticity index within the 12% maximum standard recommended by FMWH [32] for sub-base applications.

3.3 California Bearing Ratio

The results of the California Bearing Ratio (CBR) tests for the soaked (SCBR) and unsoaked (UCBR) soil samples are presented in Fig. 2. The CBR for all soaked soil samples were significantly improved for all combinations of lime and WHA in comparison with the reference sample (0:0). The CBR for unsoaked soil samples were also observed to be higher than the reference sample except for combinations 3:5 and 2:6. Although the increase in CBR values do not follow any particular trend it was observed that the combination 6:2 gave the highest value of 16.4 % and 8.56 % respectively for the unsoaked and soaked soil samples. The observed improvement in CBR may be linked to the chemical reaction between the stabilizing binder (Lime and WHA) and the soil particles, as well as the compaction of the soil matrix [33]. The gradual formation of cementitious compounds between the binders (Lime and WHA) and the soil may also have contributed to the increase in the CBR [8]. Okonkwo et al. [12] also linked the improvement in strength properties of stabilized soil to the reaction between the silica content (in WHA and laterite soil) and the calcium hydroxide content of lime, producing calcium silicate hydrates. According to Tado et al. [33], the CBR plays a vital role in evaluating the strength quality of subgrade and pavement thickness. The FMWH [32] specifies that soil samples with CBR values ranging between 7% and 20% are suitable for use as sub-base material.

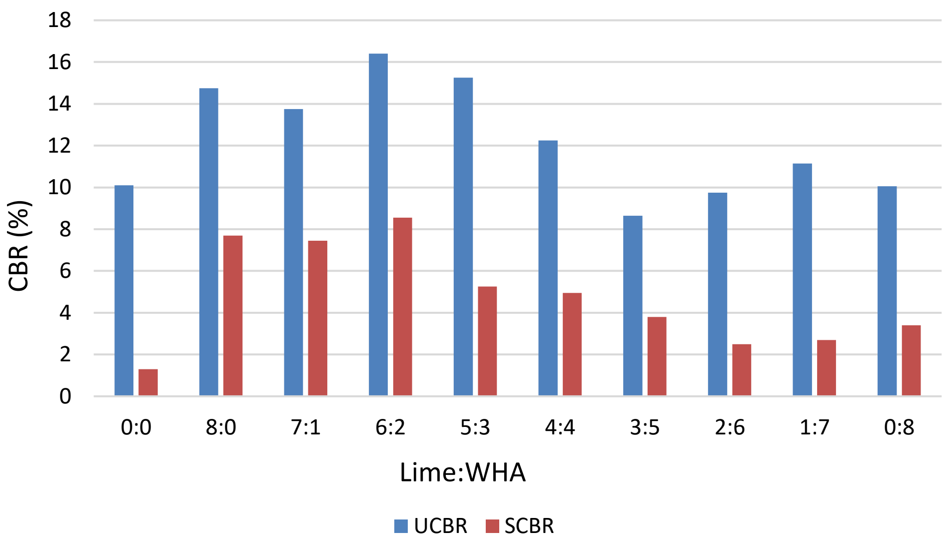


Fig. 2. Results for CBR

3.4 Unconfined Compressive Strength

The results for the Unconfined Compressive Strength (UCS) test as presented in Fig. 3, indicates that there is an increase in USC for all combinations of lime and WHA when compared with the reference sample (0:0). Although this increase did not follow any particular trend the soil sample incorporating a combination of 7: 1 had that highest increase in UCS of 39.4 %. The improvement in the strength of the stabilized soil can be attributed to the chemical changes that occur in soils blended with a higher lime content than WHA. This may have reduced the soil's capacity to hold water and increased the stability of the stabilized soil [34]. Other combinations had percentage increases in USC of 35.06, 35.69, 9.08, 16.98, 11.84, 20.57, 1.93, and 7.30 for 8:0, 6:2, 5:3, 4:4, 3:5, 2:6, 1:7, and 0:8, respectively. This improvement in the UCS aligns with the report of Moniuddin [35], where the soil was stabilized with WHA. The improvement in the UCS observed in this study could also be attributed to the formation of cementitious properties resulting from the presence of calcium hydroxide and silica compounds in the admixtures used for the stabilization process.

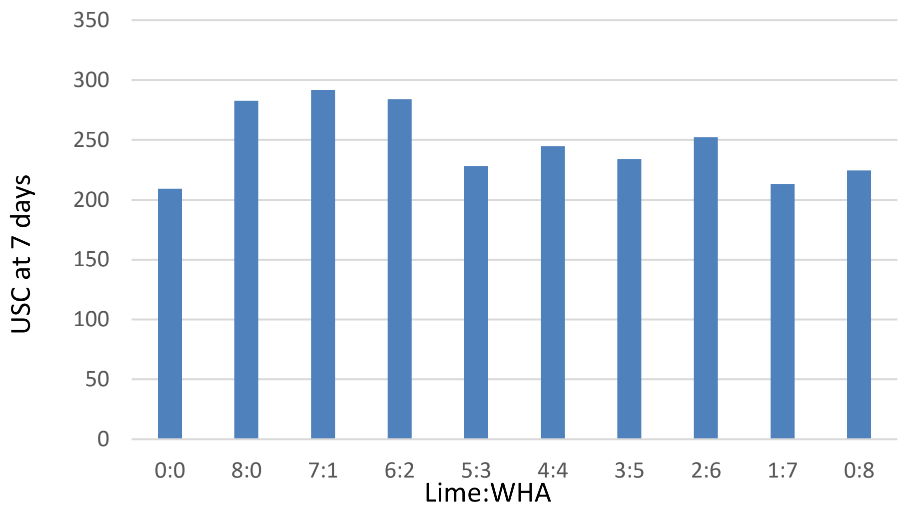


Fig. 3. Results for USC

3.5 Erodibility of the Stabilized Soil

This measures the soil resistance to erosion under traffic load. The underlying layers of the road are subjected to vibration due to vehicular movement, which tends to loosen the particles of the soil layer underneath and expose them to erosion. According to Ozmen and Tarakci [36], the soil properties determine the level of soil structure interaction under the effect of loads. The ability of the soil to resist vibration under traffic load is referred to as the Erodibility Potential (EP). The EP values for the natural and stabilized soil samples ranged from 8.76 g/min to 11.91 g/min, as presented in Table 2. This implies that improved bonding occurred as a result of using additives to stabilize the soil. The behavior indicates that as the Lime: WHA ratio moves towards a higher WHA content, there is an increase in the average weight of particles detached over time. Generally, the improved behavior of the stabilized soil mixture is due to the stabilization mechanism of lime–WHA (replacement, coagulation reaction, and exchange). The reduced erodibility potential observed with the addition of binders can be attributed to the formation of a consistent matrix resulting from the fillers' filling of the voids in the soil [37].

Table 2. Erodibility behavior of the stabilized soil

S/N	Lime: WHA	Average weight (g)	Erodibility potential (g/min)
1	0:0	119.05	11.91
2	8:0	87.56	8.76
3	7:1	92.92	9.29
4	6:2	94.47	9.45
5	5:3	96.37	9.64
6	4:4	97.29	9.73
7	3:5	98.41	9.84
8	2:6	99.63	9.96
9	1:7	109.02	10.90
10	0:8	115.06	11.51

3.6 Analysis of Variance (ANOVA) by RSM

Analysis of Variance (ANOVA) can be used to assess the contributions of linear, interaction, and quadratic terms. The significance of each term is evaluated using the Student's t-test (p-value < 0.05), and all terms with p-values less than 0.05 are considered statistically significant, while those with p-values above 0.05 are considered statistically insignificant. An ANOVA test was conducted to ascertain the effectiveness and appropriateness of the predictive model. The ANOVA results for the soil properties are presented in Tables 3 and 4. Both Tables present the contribution of the linear and interaction terms for MDD, UCS, SCBR, EP, and UCBR in achieving a significant model. The models had the following p-values of MDD, USC, SCBR, EP, and UCBR corresponding to 0.0016, 0.0259, 0.0043, 0.0002, and 0.0193, respectively. It was also observed that the input parameter A (lime) made a more significant contribution to the response compared to the input parameter B (WHA), as indicated by the p-values. A previous study by Al-swaidani et al. [38] has reported that lime plays a vital role in soil stabilization by cementing products of calcium silicate and aluminates. The Adequate Precision (AP) was used to evaluate the signal to noise ratio. A ratio greater than four is considered desirable for the model to navigate the design space.

Table 3. ANOVA for MDD, USC, SCBR, and EP

		Desired response													
Source		MDD (kg/m^3)			UCS (kN/m^2)			SCBR (%)			EP (g/min)			Remark
	DF	SS	F value	P value	SS	F value	P value	SS	F value	P value	SS	F value	P value	
Model	3	29642.90	19.98	0.0016	6303.9	6.50	0.0259	47.79	13.64	0.0043	8.83	40.56	0.0002	Significant
A	1	7218.88	14.60	0.0088	1158.9	3.58	0.1072	11.26	9.64	0.0210	4.83	66.60	0.0002	
B	1	62.98	0.1273	0.7334	36.8	0.1137	0.7474	0.0079	0.0068	0.9372	0.7897	10.89	0.0164	
AB	1	4618.36	9.34	0.0223	171.9	0.532	0.4933	0.5964	0.5107	0.5017	0.2756	3.80	0.0992	
Residual	6	2967.60			1939.9			7.01			0.4353			
Cor Total	9	32610.50			8243.9			54.80			9.26			
AP		12.01			7.33			10.62			16.90			
SD		22.24			17.98			1.08			0.27			
Mean		1720.50			246.52			4.76			10.10			
R^2		0.91			0.77			0.87			0.95			

SS: Sum of squares; DF: Degree of freedom; SD: Standard deviation; R^2: Coefficient of determination; AP: Adequate precision: A = Lime: B = WHA

Table 4. ANOVA for UCBR (%)

Source	DF	Sum of Squares	F-value	p-value	Remark
Model	2	45.76	12.39	0.0193	Significant
A-Lime	1	41.95	22.71	0.0089	
B-WHA	0	0.00			
AB	1	13.08	7.08	0.0563	
Residual	4	24.95			
Cor Total	6	53.15			
AP		8.40			
SD		1.36			
Mean		11.86			
R^2		0.86			

DF: Degree of freedom; SD: Standard deviation; R^2: Coefficient of determination; AP: Adequate precision

The following AP values of 12.01, 7.33, 10.62, 16.90, and 8.40 for MDD, USC, SCBR, EP, and UCBR, respectively, indicate that all models for the soil properties were able to adequately navigate the design space. By applying regression analysis on the experimental data, the model equations 1 to 5 were derived for all desired responses. According to Rostamiyan *et al.* [39], the positive regression coefficient in the equations corresponds to independent variables (Lime and WHA) that have contributed positively to the response. Furthermore, the negative coefficient has a negative contribution to the strength properties of the soil (MDD, USC, SCBR, EP, and UCBR). It was also observed that the SD values were substantially lower than the mean values for each model. This indicates that there is less uncertainty between the model and the experimental data used for the analysis. From these results, it can be inferred that the model is suitable for modeling and optimizing independent variables. The coefficient of determination (R^2) is another test that measures the model's fitness with the data. The value of R^2 lies in the interval (0, 1), and R^2 values above 0.5 are usually acceptable. The R^2 values for the MDD, SCBR, UCBR, UCS, and EP were 0.91, 0.87, 0.86, 0.77, and 0.95, respectively. High values for R^2 show that the regressors in the model did not explain only about 5% of the total variability. One of the unique advantages of applying RSM in modeling is the ability to model experimental data with a minimal number of experimental mixes, compared to most modeling tools.

$$MDD = +1739.0 + 3.04621*A - 17.22045*B + 3.87229*A * B \tag{1}$$

$$UCS = +209.30 +10.41527*A + 1.66594*B - 0.747186*A * B \tag{2}$$

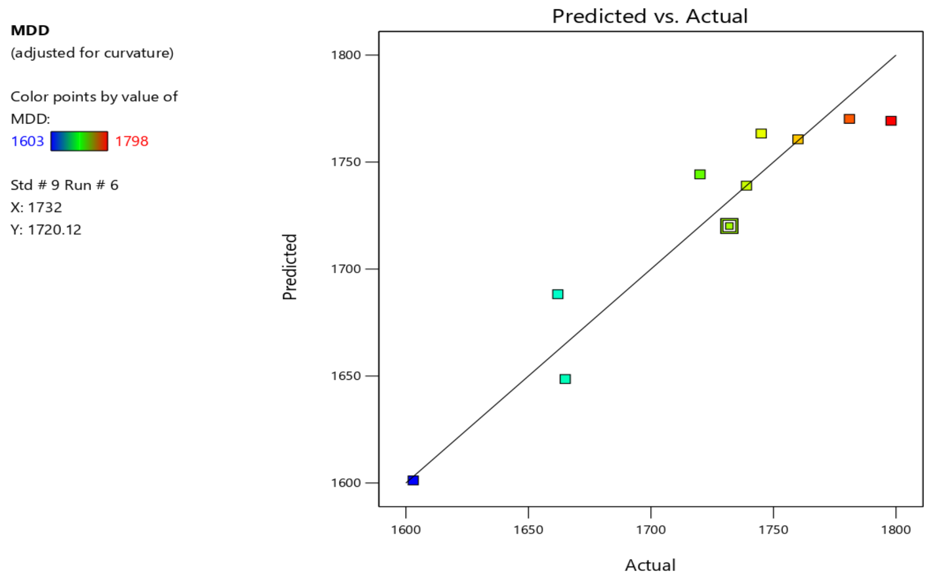
$$SCBR = +1.30 + 0.907977*A + 0.156644*B - 0.044004*A * B \tag{3}$$

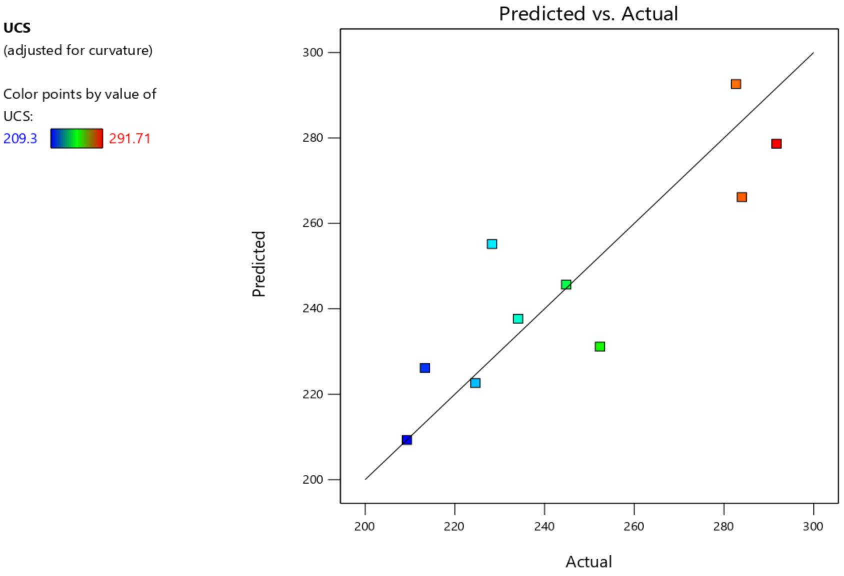
$$EP = +11.91 - 0.359879*A - 0.074212*B - 0.029913*A * B \tag{4}$$

$$UCBR = 11.75. + 7.48*A - 0.631*A*B \tag{5}$$

3.7 Verification of Model Adequacy

The RSM predictive accuracy was evaluated to assess the model's validity, as presented in Fig. 4 (a-e). The Figures illustrate the predicted versus actual plots for MDD, USC, SCBR, UCBR, and EP, respectively. For an ideally fitted model, all data points are aligned along a straight line. Considering EP, it was observed that most of the experimental data fell very close to the straight line, which explains the reason for the high R^2 of 0.95. For other properties, it was observed that there was a slight deviation of data points from the model; however, this deviation remains within the allowable limit for application, as the predicted soil properties closely match the experimental data. Consequently, for all soil properties evaluated, the models were able to accurately predict the soil's behavior, with a good correlation between the experimental and predicted values.




UCS
(adjusted for curvature)
Color points by value of
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291.71
Predicted vs. Actual
Predicted
Actual
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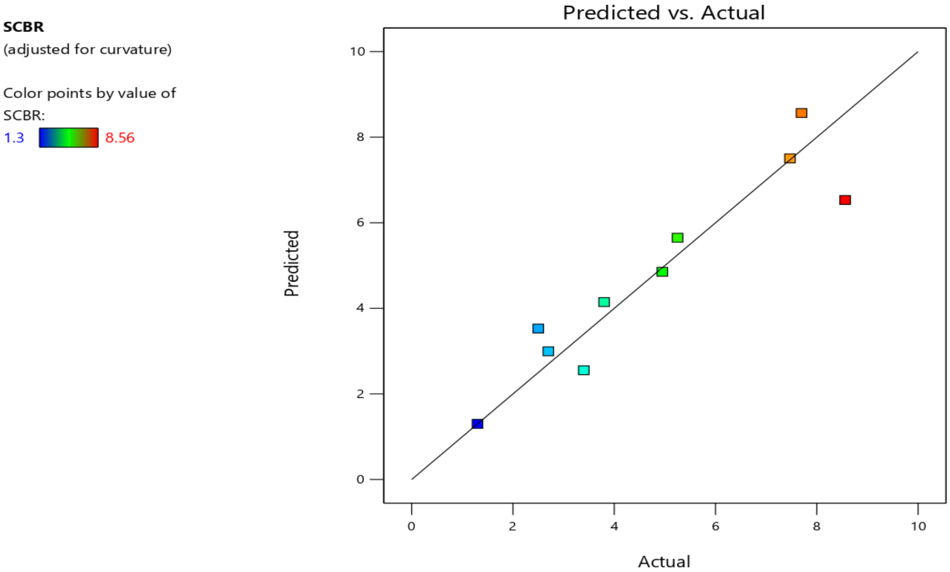
220
240
260
280
300


SCBR
(adjusted for curvature)
Color points by value of
SCBR:
1.3
8.56
Predicted vs. Actual
Predicted
Actual
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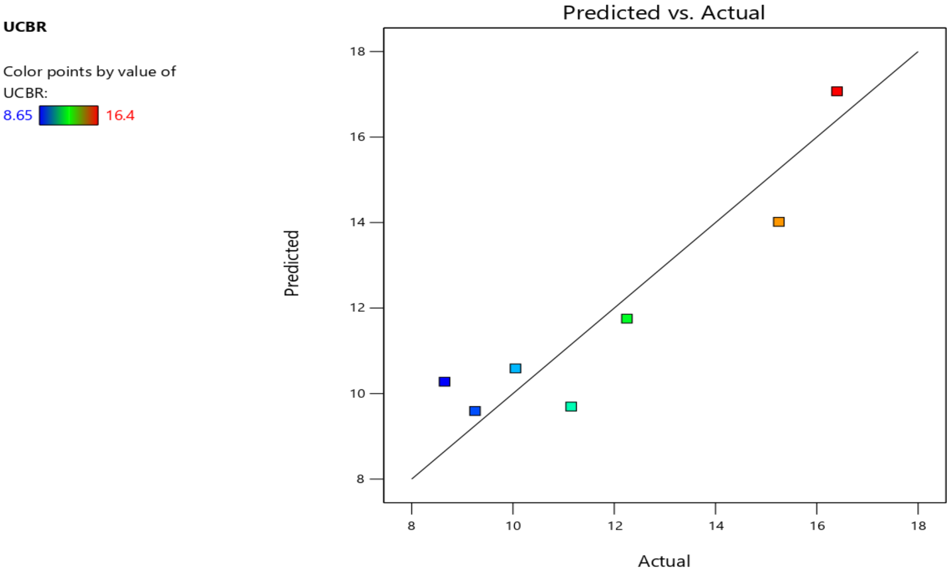
6
8
10


UCBR
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Predicted vs. Actual
Predicted
Actual
8
10
12
14
16
18

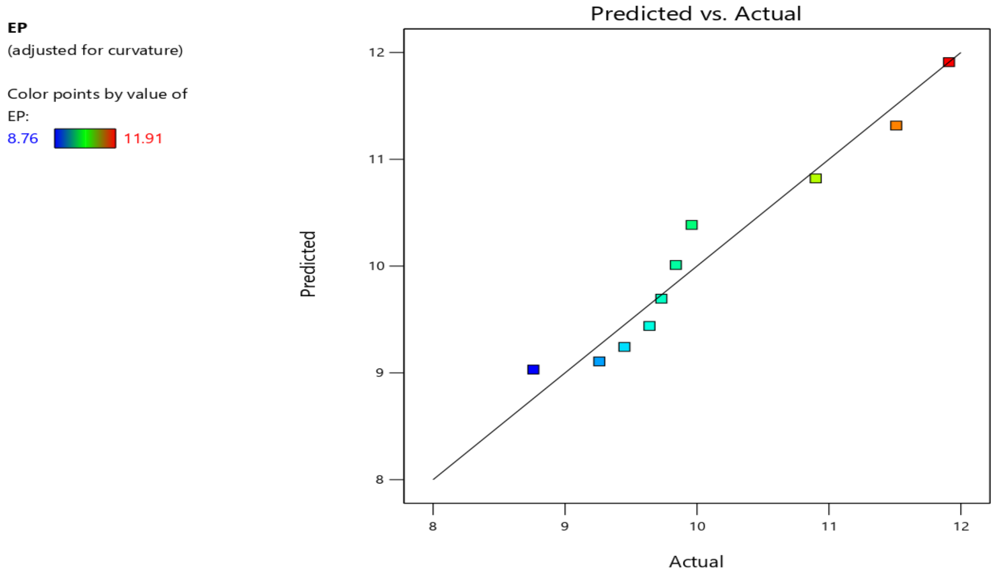
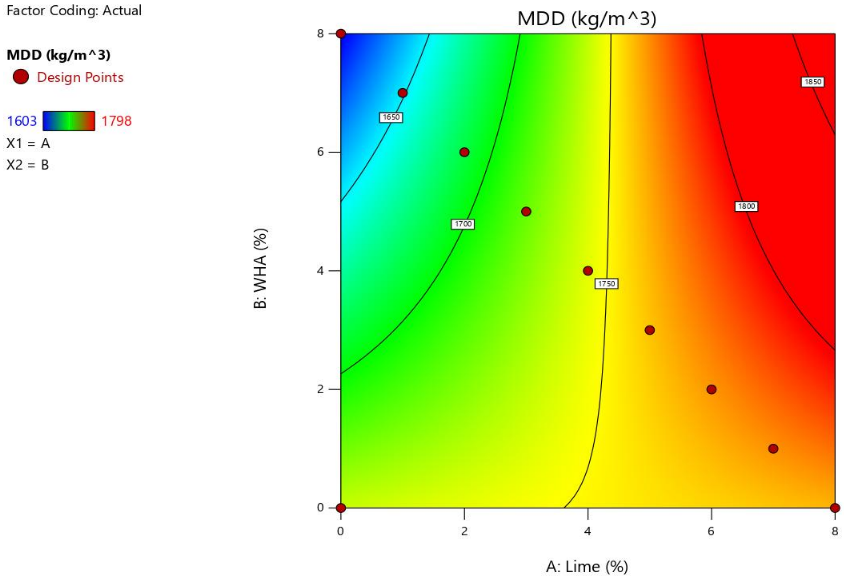


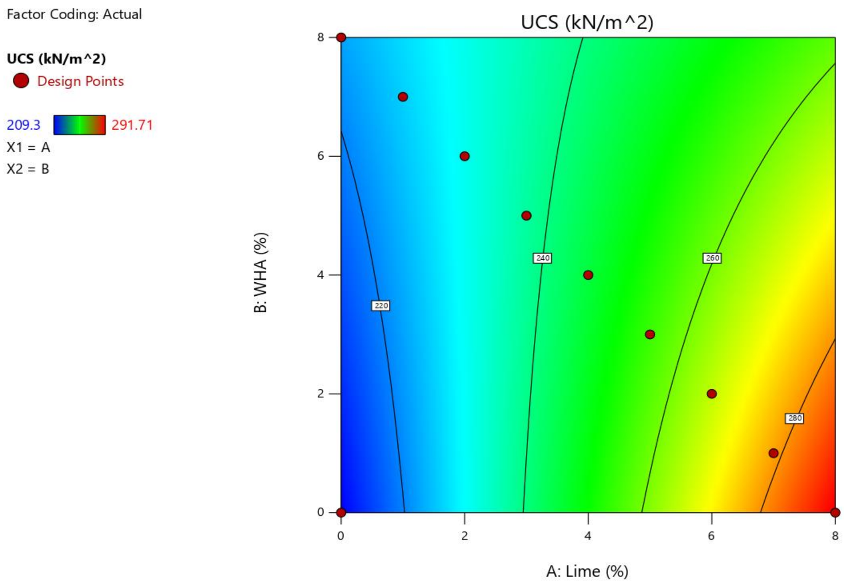
Fig. 4. RSM plots of predicted versus actual values

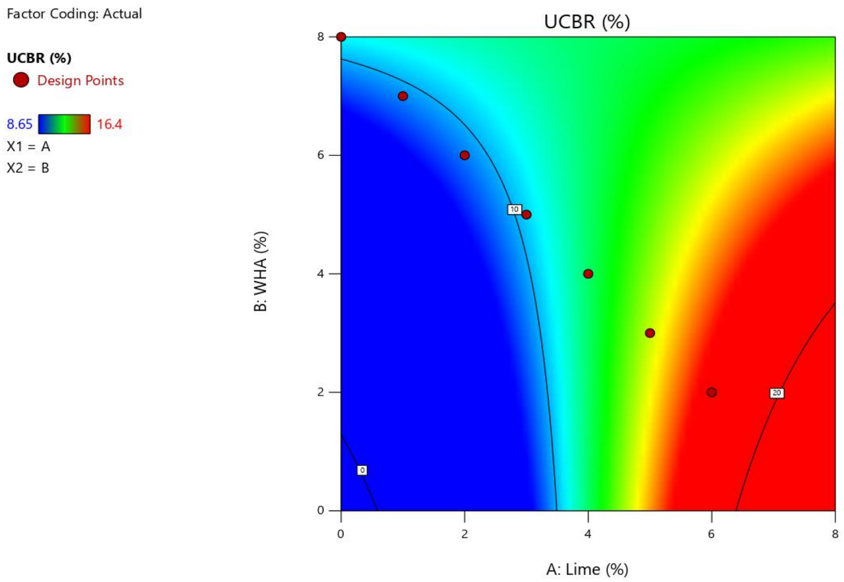
3.8 Contour Plots for RSM at Optimum Setting

RSM has been used to generate a contour plot to assess the interactive relationship between the input parameters and the desired response, as presented in Fig. 5(a-e). To understand the trend of experimental data, the contour plots were drawn as a function of two independent variables (Lime and WHA). The varying percentage of lime is presented on the x-axis, while the varying percentage of WHA is presented on the y-axis. From the contour plots of MDD, it was observed that an MDD of approximately 1800 kg/m^3 can be attained by incorporating a lime content between 6% and 8%. It can also be inferred from the plot that increased WHA content combined with reduced lime content will result in a reduced MDD. This can be attributed to WHA (2.17) having a lower specific gravity compared to lime (2.3). This aligns with Okonkwo et al. [12], who reported that the density of a material at a given volume of compaction mould is reduced when another material with a lower specific gravity replaces it. A previous study by Ojuri et al. [40] observed an improvement in MDD of the soils with 5–8% lime. The study suggested that lime is an effective stabilizing agent in enhancing soil density. Another study by Ayodele et al. [41] incorporated lime and WHA, observing that MDD can be improved with the presence of WHA and lime filling the void within the soil matrix. This compacts the soil particles closely when compactive energies are exerted on the stabilized soil. When considering the contour plots for USC, SCBR, and UCBR, a similar trend was observed, similar to that for MDD, with increasing lime content. It was observed from these plots that the USC, SCBR, and UCBR can be maximized with a lime content between 6% and 8% and a WHA content of approximately 2%. The increase in the CBR may be attributed to the formation of cementitious compounds between the binders (Lime and WHA) and the soil [8, 42]. The USC of the stabilized soil increased with the increased lime content, as illustrated in the plot.

Furthermore, the plot shows that the lime content varied between 6% and 8%, and the WHA content of approximately 2% will optimize the USC. For SCBR, the 5% threshold recommended by FMWH [32] for subgrade application can be achieved with the addition of lime content between 6% and 8%, combined with WHA content of about 2%, as displayed on the contour plot. Lastly, from the contour plot of EP, it was observed that reduced lime content and increased WHA content increase the possibility of soil erosion under traffic loading. This clearly indicates that at higher lime content, the soil presents a better resistance to loss of strength due to vibration. From this result, it could be inferred that the durability of the soil can be enhanced through improved bonding with the incorporation of the additives.


Factor Coding: Actual
MDD (kg/m^3)
Design Points
1603
1798
X1 = A
X2 = B
MDD (kg/m^3)
1650
1700
1750
1800
1850
B: WHA (%)
A: Lime (%)


Factor Coding: Actual
UCS (kN/m^2)
Design Points
209.3
291.71
X1 = A
X2 = B
UCS (kN/m^2)
220
240
260
280
B: WHA (%)
A: Lime (%)


Factor Coding: Actual
UCBR (%)
Design Points
8.65
16.4
X1 = A
X2 = B
UCBR (%)
0
10
20
B: WHA (%)
A: Lime (%)

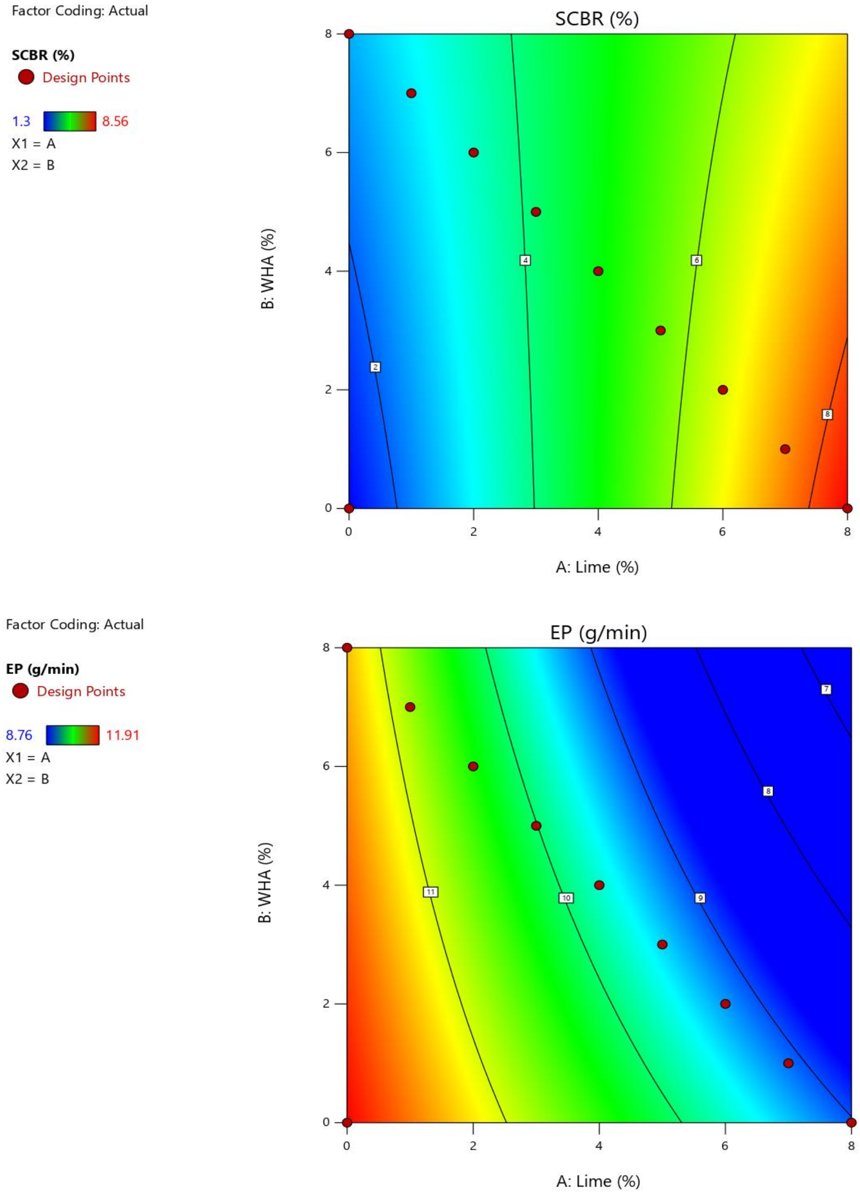


Fig. 5. Contour plots for the strength properties of the soil

4. Conclusions and Recommendations

4.1 Conclusions

The study promotes sustainable construction by utilizing wheat husk for soil stabilization. The current study presents applicable models for predicting the behavior of soil stabilized with different mixes of WHA and lime, which can be particularly utilized in the design or construction of road pavement. From the findings of the study, the following conclusions were drawn:

- The MDD of the soil increased with the addition of specific combinations of lime and WHA compared to the non-stabilized soil. The MDD of 1798kg/m^3 for 6 % lime and 2 % WHA displayed improved soil compaction with the incorporation of both stabilizers.
- The consistency limits, as evaluated using the LL and PL, increased for all combinations of lime and WHA compared to the non-stabilized soil.
- The CBR and UCS at a 7-day curing period increased due to the formation of cementitious properties resulting from the incorporation of lime and WHA. The highest CBR values for the combination of 6 lime and 2 WHA were 16.4% and 8.56%, respectively, for the unsoaked and soaked soil samples.

- The EP values for the stabilized soil samples ranged from 8.76 g/min to 11.51 g/min. This demonstrated that the incorporation of lime and WHA improved the soil's resistance to vibration under traffic loads.
- The lime content was identified as a very significant factor in predicting the soil properties, and p-values less than 0.05 were considered statistically significant. In addition, the models' p-values for all desired responses were 0.0016, 0.0259, 0.0043, 0.0002, and 0.0193 for MDD, USC, SCBR, EP, and UCBR, respectively. This provides an avenue for predicting the properties of stabilized soil without the need for rigorous laboratory experiments.
- A general trend of improvement in the MDD, USC, SCBR, EP, and UCBR of the stabilized soil, with a lime content varying between 6% and 8% and a WHA content of approximately 2%, was observed.

4.2 Recommendation

It is recommended that other available unutilized residues from farm crops that can be useful in soil stabilization be investigated. Further research on the recycling of other agricultural waste for sustainable construction purposes will promote an eco-friendly environment.

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