Influence of Compaction Variables and grain size composition on Unconfined Compressive Strength model of Sand-Clay mixtures

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ABSTRACT : *Assessing the combined influence of compaction variables and grain size composition on the unconfined compressive strength (UCS) model of mixed blended soils is necessary for cost-effective and reliable construction outcomes. River sand was blended with clay in the proportion: 0, 20, 30, 40, 50 and 60% by weight of clay. Laboratory experiments were carried on the sand-clay mixture to determine the grain size distribution, consistency, compaction properties and the unconfined compressive strength. The results of the maximum dry density (MDD), optimum moisture content (OMC), grain size composition (fine and sand particles) and UCS were used to generate models under two compaction efforts using Response Surface Methodology (RSM) with MDD, OMC and grain size as independent variables and UCS as the response factor. The model developed showed high prediction confidence level of over 96% across mixtures. There was a substantial level of significance for the model comprising of MDD and OMC, but much enhancement was recorded when grain size distribution was introduced into the model. R^2 values between 0.96 and 0.99 were recorded across the four models generated*

I.   INTRODUCTION

The engineering behavior of soil mixtures, particularly sand-clay blends, is critical in various geotechnical applications, including earth retaining structures, road pavements, and foundation beds (Onyelowe *et al.*, 2022). Among these behaviors, the Unconfined Compressive Strength (UCS) stands out as a key parameter for assessing soil stability and integrity, offering valuable insights into a soil's capacity to resist axial loads without lateral confinement.

Compaction characteristics, notably the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), play a pivotal role in achieving desirable UCS values. These characteristics are largely governed by the level of compaction effort applied as well as the inherent soil composition, including the proportions of sand and clay (Yamus *et al.*, 2019; López *et al.*, 2024). However, despite the significance of UCS in evaluating soil performance,

limited studies have examined the combined influence of compaction variables and grain size composition on the UCS of mixed soils (Do *et al.*, 2021). This underscores the need to investigate the synergistic effects of these factors under varying compaction energies.

Against this backdrop, the present study explores the influence of compaction variables and grain size composition on the UCS of sand-clay mixtures. Employing Response Surface Methodology (RSM), the study develops a predictive model that captures the interactions among these variables and identifies optimal compaction parameters for achieving enhanced UCS. The application of RSM allows for systematic evaluation of multiple factors and their interdependencies, providing a robust framework for optimizing soil compaction strategies.

Recent studies have highlighted the role of compaction effort and soil composition in influencing UCS and related properties. For instance, Pham *et al.* (2021) employed Artificial Neural Networks (ANN) to predict UCS based on selected soil parameters, revealing that cement content and the proportion of particles passing the 0.5 mm sieve were the most influential factors. Similarly, Xu *et al.* (2023) demonstrated that incorporating sand into clay soils notably improved compaction characteristics and strength, with optimal results at a 20% sand content. Moreover, research by Aziz (2023) and Alnmr *et al.* (2024) emphasized the critical influence of grain size composition on soil strength. Alnmr *et al.* (2024), using machine learning approaches, identified a 30% sand blend as a key threshold for enhancing the strength and stiffness of expansive soils, with ANN-GMDH models yielding the highest predictive accuracy.

This research is both timely and relevant, given the growing demand for sustainable and resilient infrastructure. A deeper understanding of how compaction parameters and grain size distribution influence UCS is essential for designing durable structures, particularly in regions characterized by heterogeneous soil profiles (López *et al.*, 2024; Do *et al.*, 2021). Insights from this study can inform more efficient compaction practices, thereby reducing the risk of structural failures in road construction and earth-retaining systems. Additionally, by integrating RSM, this work offers a novel approach to modeling the complex relationships between compaction variables and grain size composition, ultimately supporting cost-effective and reliable engineering solutions.

II.   MATERIALS AND METHODS

2.1 Materials

The clay soil was sourced from Minna, Nigeria, with GPS coordinates of longitude 9∘35'1.1" N and latitude 6∘32'46.6" E. The disrupted sample was taken at a depth ranging from 1.0 to 1.3 meters below the surface of the ground. Table 1 displays the key features of the clay soil. The clay soil sample demonstrates particular physical characteristics crucial to its designation as CH (high plasticity clay) under the Unified Soil Classification System (USCS), with 84.00 % of particles smaller than 0.075 mm categorizing the soil as mostly fine-grained.

The study's river sample was acquired from a nearby provider in Minna, Niger State, Nigeria. Table 2 provides information on the characteristics of the river sand. The river sand with a specific gravity of 2.69, with majority of the particle passing sieve 2

mm, is classified as well graded sand (SW) according to the Unified Soil Classification System (USCS). Table 3 displays the oxide composition of both the clay and river sand. Both the clay soil and river sand were tested according to the standards of BS 1377 and 1924 (1990). Plate 1 display the material used in the study with A and B, corresponding to sand and clay respectively.

A.   B.

Plate 1: Materials used in the study

2.2 Methods

The river was mixed with the clay soil in varying proportions of 0, 10, 20, 30, 40, 50, and 60 % by weight. Laboratory tests were carried out on the clay, sand and sand-clay mixtures, including sieve analysis, Atterberg limits, compaction tests and unconfined compressive strength tests. The sand-clay mixture underwent a sieve analysis to identify the distribution of grain sizes. The method utilized was compliant with BS 1377 (1990) section 2. The Atterberg limits for the mixed samples were identified following the guidelines outlined in BS 1377, which detail the process for determining soil liquid limit, plastic limit, and plasticity index. The compaction test followed BS 1377 (1990) part 4, using British Standard Heavy (BSH) and British Standard Light energy level, as specified. The unconfined compressive strength (UCS) of the clay and sand-clay mixtures was determined in accordance with the procedures outlined in BS 1377 (1990), ensuring standardized testing for reliable assessment of strength characteristics.

The Response Surface Methodology was performed using the numerical values of the compaction characteristics (Table 5) and the grain size distribution of the sand-clay mixtures (Table 4) in order to assess the connections between the independent variables and the dependable variable - unconfined compressive strength test (Figure 4). RSM is highly efficient in detecting how independent variables and their interactions impact a response, enabling fine-tuning (Khuri and Mukhopadhyay, 2010). The methodology was adopted in three main stages: creating the experiment (feeding of data), determining the coefficients of the desired model, and identifying the best conditions.

Basically, the second-order polynomial was utilized and is expressed as:

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j}^{k} \beta_{ij} X_i X_j + \varepsilon$$

where: Y is the response variable; β_o is the intercept term; β_i represents the linear coefficients; β_{ii} denotes the quadratic coefficients; β_{ij} represents the interaction coefficients, and ε accounts for the experimental error.

Table 1: Basic Characteristics of the Clay Soil (Godwin *et al.*, 2024)

Characteristics	Value	
Natural Moisture content (%)	16	
Percent passing No. 4 sieve (2.00 mm)	98.93	
Percent passing sieve 0.075 mm	84.00	
Liquid limit (%)	58.00	
Plastic limit (%)	16.50	
Plasticity index (%)	41.50	
Specific gravity, G_s	2.54	
USCS classification	CH	
AASHTO classification	A-7-6	
Colour	Dark brown	
	BSH	**BSL**
Maximum dry density, MDD (g/cc)	1.848	1.625
Optimum moisture content, OMC (%)	16	19

Table 2: Basic Properties of the River Sand (Godwin *et al.*, 2024)

Property	Description/value	
Percent passing No. 4 sieve (2.00 mm)	89.60	
Percent passing sieve 0.075 mm	3.52	
Specific gravity, G_s	2.69	
USCS classification, $C_c = 3.33$	SW	
	BSH	**BSL**
Maximum dry density, MDD (g/cc)	1.884	1.884
Optimum moisture content, OMC (%)	11	18

Table 3: Oxide composition of Clay soil and Sand (Godwin *et al.*, 2024)

Oxide	Clay soil (%)	Sand (%)
SiO_2	56.30	40.25
Al_2O_3	29.69	20.74
Fe_2O_3	4.64	30.87
MnO	0.09	0.07
CaO	1.60	0.42
P_2O_5	-	-
K_2O	0.89	0.66
TiO_2	1.19	1.35
MgO	4.65	4.84
Na_2O	0.89	0.65
SO_3	0.12	0.13
LOI	0.03	0.04

LOI = Loss on ignition

III.   RESULTS AND DISCUSSION

3.1 Particle size distribution

The particle size distribution indicates that the soil predominantly consists of fines, sand, and gravel, with fines and sand being the primary components (see Table 4 and Figure 1). The proportion of fines tends to decrease as the sand content increases, transitioning to a sand-dominated gradation at 50% S and 60% S.

Table 4: Grain size percentages

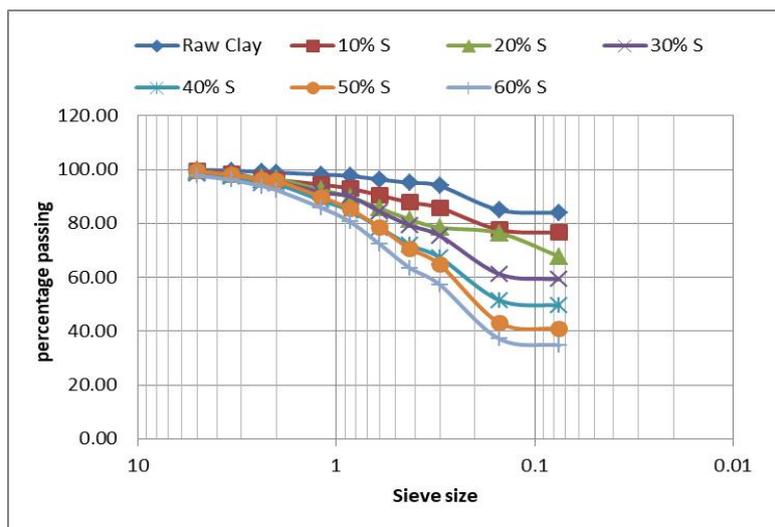|	Clay	10% S	20% S	30% S	40% S	50% S	60% S
Gravel (%)	0.10	0.53	0.67	1.43	1.33	0.60	2.20
Sand (%)	15.9	22.84	31.63	39.3	49.13	58.5	67.33
Fine (%)	84.00	76.63	67.70	59.27	49.54	40.9	34.87

Fig. 1: Combined grain size distribution curve of the sand-clay mixture

3.2 Consistency limit

As shown in Figure 2, the pure clay sample exhibits high plasticity, with a liquid limit (LL) of 58.0% and a plasticity index (PI) of 41.5%, indicating a significant susceptibility to volume changes with moisture variations. However, the incorporation of river sand leads to a continuous decline in both LL and PI. For instance, adding 10% sand reduces the liquid limit by 29.0% and the plasticity index by 39.1%. At 20% sand content, the LL decreases further by 34.9%, while the PI drops by 47.0%. When 30% sand is introduced, the liquid limit sees a 40.3% reduction, reflecting a marked improvement in the clay's engineering properties. A 40% sand addition results in a 40.5% decrease in LL and a 49.1% reduction in PI. Further increasing the sand content to 50% decreases both the LL and PI by 54.9%. The most significant change is observed at 60% sand content, where the liquid limit drops by 49.3% and the plasticity index by 68.8%. This reduction in plasticity aligns with the findings of Dasgupta (2014), Louafi and Bahar (2012), and Kollaros and Anthanasopoulou (2017). Overall, the plasticity index consistently decreases with increasing sand content, with the most substantial improvement occurring in the CL + 60% S mixture.
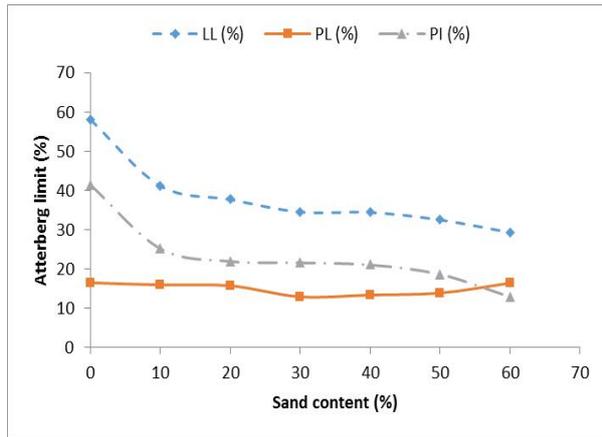
Fig. 2: Atterberg limit of sand-clay mixture

3.3 Compaction characteristics

Figure 3a illustrates the MDD trend observed at different sand content levels. The pattern showed a rise in maximum dry density (MDD) as sand content increased, with R2 values of 0.979 and 0.926 for modified proctor (BSH) and standard proctor (BSL) respectively. In contrast, Figure 3b displayed a decline in the OMC result as the sand content percentage varied, with R2 values of 0.967 and 0.877 for BSH and BSL compaction efforts, respectively. The R^2 signifies a strong relationship between MDD and sand content as well as between OMC and the latter. Clay soil with no sand has a lower maximum dry density and higher optimum moisture content, resulting in higher density during the Modified Proctor test because of increased compaction energy.

The maximum dry density rises when more sand is added, reaching its highest point at 50% sand for BSH and 60% for BSL experiments. The rise in MDD with sand content was also noted by Al Rawi *et al.* (2018), as well as Kollaros and Anthanasopoulou (2017). The rise in MDD suggests better soil organization and cohesion between particles, leading to a more compact material. The BSH modified Proctor test consistently yields higher MDD values compared to the BSH Standard Proctor test, as a result of the increased compaction energy. The addition of 50% CL results in the highest MDD of 2.181 g/cc for BSH, roughly 1.2 times more than that of raw clay. The Optimum Moisture Content (OMC) decreases with increasing sand content, reaching a minimum of 9.60% for BSH and 11.20% for BSL. Reduced OMC values mean that a smaller amount of water is required to reach optimal density,

benefiting construction by lessening the chances of water-related problems like swelling and shrinkage. The decrease in organic matter content as sand content increases indicates the mixture's enhanced drainage and decreased water retention ability (Alnmr and Ray, 2021). Additionally, the effectiveness of compaction increases with the presence of sand, as shown by the elevated MDD and OMC values. These findings indicate that the addition of sand to clay soils can greatly improve their appropriateness for serving as backfill material (Al-Taie and Ahmed, 2024; Feng *et al.*, 2023). The combination of 50% and 60% sand displays the top MDD and minimum OMC, indicating the perfect amount of sand needed for BSH and BSL. In MDD, there was an 18.02% rise for BSH and a 26.15% increase for BSL, while for OMC with 50% sand content, BSH saw a decrease of 39.94% and BSL saw a decrease of 40.79%. On the other hand, 17.42% and 28.31% increase was recorded for BSH and BSL of the MDD and 40.0% and 41.05% decrease in OMC for BSH and BSL respectively of 60% sand content.
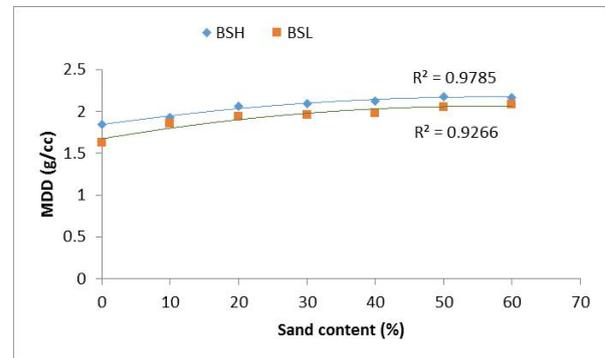

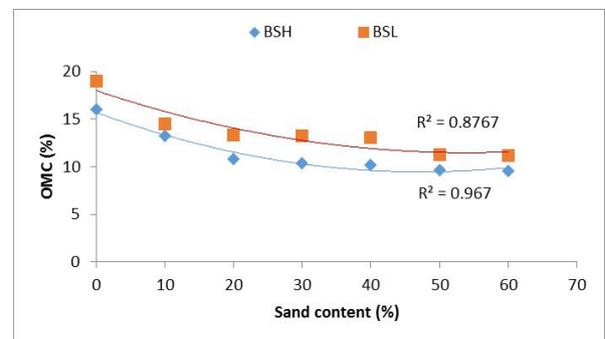**Fig. 3a: Variation of MDD with varying sand content in clay**

Fig. 3b: Variation of OMC with sand content varying sand content in clay

3.4 Unconfined Compressive Strength

The unconfined compressive strength (UCS) is a measure of the load-bearing capacity of a soil when subjected to axial loading without lateral confinement. The column chart in Figure 4 provided shows the UCS values for various sand-clay mixtures under both Standard Proctor (BSL) and Modified Proctor (BSH) compaction efforts. Pure clay has the lowest UCS under both compaction efforts. This low UCS is characteristic of clay due to its fine-grained structure and lower shear strength. Adding 10% sand increases the UCS. The BSH UCS increases by approximately 3.6%, while the BSL UCS increases by 14.8%. The presence of sand particles enhances the load-bearing capacity of the mixture. With 20% sand, the UCS increases significantly under BSH, by approximately 39.8%. However, the BSL UCS remains almost unchanged with a negligible decrease of 0.2%. At 30% sand, the UCS under BSH shows a slight decrease of approximately 1.8% compared to the 20% sand mixture, but is still significantly higher than pure clay. The BSL UCS is almost unchanged with a negligible increase of 0.2%. The mixture maintains higher strength than pure clay but does not exhibit significant improvement over the 20% sand mixture. With 50% sand, the UCS under BSH increases significantly, by approximately 65.6%. The BSL UCS also shows a notable increase of 46.2%.

In general, the UCS increases as the sand content increases. Kollaros and Anthanasopoulou (2017) indicated an increase in UCS with sand content with peak value at 60% sand under light compaction effort. This increase in UCS is due to the enhanced load-bearing capacity provided by the sand particles (Guan and Madabhushi, 2022). For example, the BSH UCS increases from 120.51 kPa (pure clay) to 199.49 kPa (CL + 50% sand), an increase of approximately 65.6%. Similarly, the BSL UCS increases from 60.63 kPa to 105.24 kPa, an increase of approximately 73.5% for CL + 60% Sand. For engineering application, the pure clay's low UCS makes it less suitable for applications requiring high compressive strength, such as foundations and load-bearing structures. CL + 10% Sand to CL + 40% Sand mixtures could be used in applications where moderate compressive strength is required. CL + 50% Sand to CL + 60% Sand mixtures are more suitable for applications where high compressive strength is required.
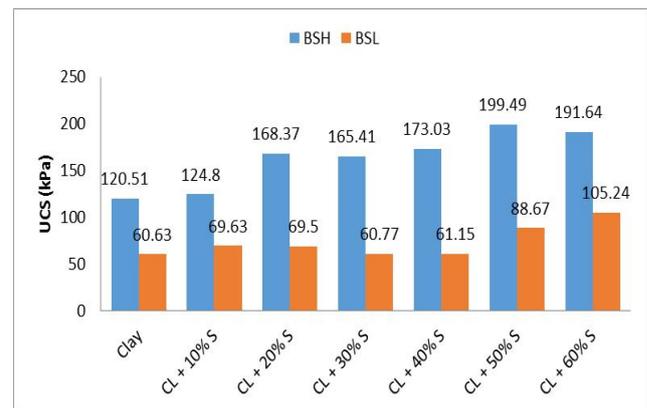

Fig. 4: Variation of unconfined compressive strength with varying sand content

3.5 Influence of compaction variables and grain size on unconfined compressive strength

Table 5 highlights the models generated using Response Surface Methodology with maximum dry density (MDD), optimum moisture content (OMC), fine particles (F) and sand particles (S) as variables, while the unconfined compressive strength (UCS) as the response factor. The R^2 values ranging from 0.96 – 0.99 expresses the effect of these parameters on the UCS, considering the high confidence level obtained for both compaction energy. The result reveals a strong relationship between these parameters with UCS. The R^2 values also indicated the importance of these parameters in UCS prediction. The introduction of grain size further enhances the model accuracy with an increase in confidence level of 3% across board.

Table 5: Unconfined compressive strength model

Model		Variables	R^2 value	Energy level
UCS	= 128040 - 95283 MDD - 5299 OMC + 17775 MDD* MDD + 54.6 OMC* OMC + 1971 MDD*OMC	MDD, OMC	0.96	BSH
UCS	= 12843 - 13942 MDD + 202 OMC + 3477 MDD* MDD - 9.03 OMC*OMC + 4 MDD*OMC	MDD, OMC	0.98	BSL
UCS	= 518.5 - 2121 MDD + 51.88 OMC + 4.966 Fine + 6.768 Sand + 710.1 MDD*MDD - 1.492 OMC*OMC	MDD, OMC, F and S	0.99	BSH
UCS	= 9448 - 10353 MDD + 152.3 OMC + 2.352 Fine + 2.199 Sand + 2566 MDD*MDD - 6.802 OMC OMC	MDD, OMC, F and S	0.99	BSL

for BSH and BSL compaction effort

IV.   CONCLUSION

The study demonstrated a high level of reliability for the developed unconfined compressive strength (UCS) models of sand-clay mixtures incorporating compaction variables (maximum dry density and optimum moisture content) as well as grain size composition (sand and fine particles) across both compaction efforts. The models achieved excellent predictive performance, with coefficient of determination (R^2) values ranging from 0.96 to 0.99, underscoring the strong correlation between the selected parameters and UCS.

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