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Original Research Article

Durability Assessment of Cassava Starch-Stabilized Lateritic Soils Using Scheffé's Regression: A Sustainable Soil Treatment Perspective

Bright Worlu[1], Ohwerhi Kelly Erhiferhi[2*], Nwaobakata Chukwuemeka[2]

[1]Centre for Geotechnical and Coastal Engineering Research, CGCER, University of Port Harcourt, Port Harcourt, Rivers State
[2]Department of Civil Engineering, University of Port Harcourt, Port Harcourt, Rivers State

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***Corresponding author:** Ohwerhi Kelly Erhiferhi
Department of Civil Engineering, University of Port Harcourt, Port Harcourt, Rivers State

Abstract

This study investigates the durability of cassava starch-stabilized lateritic soils subjected to cyclic wet–dry loading, using unconfined compressive strength (UCS) and indirect tensile strength (ITS) retention as key durability measures. Lateritic soils, widely used in tropical subgrade construction, suffer strength loss due to moisture fluctuations. Conventional stabilizers like cement and lime, although effective, have significant environmental drawbacks. Cassava starch, a biodegradable and abundant biopolymer, offers a sustainable alternative with promising soil-binding properties. Twelve mix designs, incorporating varying proportions of lateritic soil, cassava starch (0–10%), and water-to-solids ratio (12–16%), were prepared and cured for 28 days before undergoing 12 wet–dry cycles to simulate environmental stress. UCS retention ranged from 69.68% to 91.24%, and ITS retention from 71.79% to 92.91%, with the best-performing mix surpassing ASTM and AASHTO durability criteria and Nigerian subgrade strength requirements. Scheffé's (3,2) mixture regression models accurately predicted durability outcomes, achieving R^2 values above 99% and passing F-tests for model adequacy at a 5% significance level. These findings confirm cassava starch's effectiveness in enhancing the mechanical resilience and moisture durability of lateritic soils, supporting its application as a green stabilizer for sustainable infrastructure. The study presents a validated, data-driven framework for optimizing bio-based soil stabilization, advancing eco-friendly geotechnical practices and climate-resilient road construction.

Keywords: durability, unconfined compressive strength retention, indirect tensile strength retention, Scheffe's regression, cassava starch.

1. INTRODUCTION

Lateritic soils are widely distributed across tropical regions and constitute a major source of material for construction, particularly in road infrastructure and foundation works. In countries like Nigeria, Ghana, and other parts of West and Central Africa, lateritic soils are extensively used as subgrade and subbase materials due to their widespread availability and favorable engineering characteristics when appropriately stabilized (Adebisi *et al.,* 2020; Bello *et al.,* 2018). These soils are formed through intensive and prolonged weathering of parent rocks under hot and humid climatic conditions, resulting in soils rich in iron and aluminum oxides (Gidigasu, 1976; Osinubi *et al.,* 2019). Their relatively good bearing capacity and natural binding properties make them attractive for low-cost construction applications.

However, untreated lateritic soils are often deficient in strength and durability, particularly under cyclic wet–dry conditions that typify tropical climates, leading to progressive deterioration and loss of serviceability (Muntohar *et al.,* 2016). Exposure to repeated moisture fluctuations weakens inter-particle bonds, reduces matric suction, and leads to volumetric changes that compromise long-term structural stability (Amadi & Osunde, 2020). As noted by Bello et al. (2021), the unconfined compressive strength (UCS) of natural lateritic soils can reduce by over 40% after three wet–dry cycles, a decline which directly undermines their performance in subgrade applications.

In response to these challenges, researchers have increasingly explored chemical stabilization techniques to enhance the mechanical performance and moisture resistance of lateritic soils. Approaches such as bio-based additives (e.g., cassava and corn starch), lime, cement, and pozzolanic waste materials have been investigated for their capacity to improve strength retention under environmental stress (Akinwumi *et al.,* 2021; Jorin *et al.,* 2022). Thus, while lateritic soils remain integral to infrastructure development across tropical regions, their untreated form is highly vulnerable to environmental degradation. Addressing this limitation through sustainable soil treatment strategies is crucial for ensuring longevity, cost-effectiveness, and environmental compatibility in geotechnical and civil engineering applications.

Traditional soil stabilization techniques frequently rely on the use of cement, lime, or bitumen. While these methods are effective in enhancing the mechanical and durability characteristics of soils, they are energy-intensive and associated with high carbon emissions, thus posing environmental and sustainability concerns (Amadi & Osinubi, 2021). Cement production alone accounts for approximately 7–8% of global CO_2 emissions due to the calcination process and high-temperature kiln operations (Habert *et al.,* 2020). Similarly, lime stabilization contributes significantly to environmental degradation due to energy consumption in limestone calcination and particulate emissions during handling and application (Latifi *et al.,* 2016).

Consequently, the growing need to mitigate the environmental footprint of construction practices has led to a paradigm shift toward eco-friendly and sustainable stabilization agents. This has prompted increased research into natural polymers and agricultural by-products, such as starches, gums, and lignocellulosic fibers, as viable alternatives to traditional chemical stabilizers. These bio-based materials are not only renewable and biodegradable but also often sourced from agricultural waste, contributing to circular economy principles (Horpibulsuk *et al.,* 2021; Shah *et al.,* 2023).

Starches derived from plants such as cassava, corn, and potato have been shown to improve soil strength and water retention through bio-binding mechanisms, promoting cohesion among soil particles (Jorin *et al.,* 2022). Studies have reported that starch-based stabilizers can enhance unconfined compressive strength (UCS), reduce plasticity, and increase resistance to erosion and water ingress, especially under cyclic wet–dry conditions (Akinwumi *et al.,* 2021). In addition, natural gums such as guar and xanthan have demonstrated promising results in improving the tensile and shear strength of soils by forming gel-like matrices that stabilize the soil structure (Latifi *et al.,* 2016). Furthermore, agricultural residues such as rice husk ash, bagasse ash, and coconut coir have been evaluated for their pozzolanic reactivity and mechanical reinforcement potential in soil matrices (Basha *et al.,* 2005; Jha & Sivapullaiah, 2016). These bio-based stabilizers are not only low-cost but also enhance the environmental profile of soil treatment processes, especially in regions where agricultural waste management remains a challenge.

Cassava starch, an abundant and renewable bio-resource in many tropical regions, has recently gained attention as a sustainable soil stabilizer. Extracted from the tuberous roots of Manihot esculenta, cassava starch is biodegradable, non-toxic, cost-effective, and widely available, particularly in sub-Saharan Africa, where cassava is cultivated extensively for food and industrial uses (FAO, 2020). Its polysaccharide-rich structure enables it to function as a natural binder, enhancing the cohesion among soil particles and improving the structural integrity of treated soils.

Empirical studies have demonstrated that cassava starch can significantly improve the engineering properties of problematic soils, including plasticity, unconfined compressive strength (UCS), and durability under environmental stressors. For instance, Muntohar *et al.,* (2017) investigated the use of natural biopolymers, including cassava starch, in stabilizing expansive soils. They found that cassava starch significantly improved the unconfined compressive strength (UCS) and reduced swell potential when used at 5–7% dosage. Treated samples also displayed enhanced stiffness and reduced moisture sensitivity, indicating their potential for application in road embankments and low-volume pavements. Oluremi and Jimoh (2020) examined the effect of cassava starch on lateritic soil used in subbase layers. Their results showed a progressive increase in UCS from 212 kN/m² in untreated soil to over 390 kN/m² in soil treated with 6% cassava starch after 28 days. Moreover, water absorption decreased by more than 20%, signifying increased water resistance and durability against wet–dry cycles. Edeh and Akinmusuru (2020) reported that the inclusion of cassava starch at optimal dosages increased the UCS of lateritic soil by over 40% after 28 days of curing, demonstrating performance comparable to traditional chemical stabilizers. Akinwumi and Oladele (2021) evaluated cassava starch in comparison with cement and lime for the stabilization of tropical red clay. The starch-treated specimens exhibited strength improvements comparable to those of lime-stabilized samples, while also demonstrating lower environmental impact and reduced energy consumption. Notably, cassava starch contributed to improved cohesion and aggregate binding through a film-forming mechanism, thereby reducing microstructural voids and permeability. Olaofe *et al.,* (2021) studied the performance of cassava starch and plantain peel ash blend in stabilizing sandy clay. They observed that the binary blend at 5% cassava starch and 10% ash produced a synergistic effect, with UCS exceeding 500 kN/m² and improved resistance to cracking and erosion. This suggests cassava starch may also serve effectively in hybrid stabilizer systems. Alhassan and Mustapha (2021) reported that lateritic soils treated with 4–6% cassava starch demonstrated marked increases in UCS and resilience under cyclic wet–dry conditioning. The starch-treated soils retained over 75% of their initial strength after three cycles, highlighting their enhanced durability and suitability for subgrade applications in tropical climates. Basha *et al.,* (2022) found that cassava starch reduced soil plasticity index and swelling potential while improving water resistance, thereby enhancing the long-term durability of stabilized soils under cyclic wet–dry exposure. Maharaj and Ali (2022) conducted a microstructural and mechanical study on biopolymer-treated soils in Guyana and found that cassava starch altered the soil's pore structure, increasing UCS and California Bearing Ratio (CBR) values by over 60%. Scanning electron microscope (SEM) analyses revealed that the starch filled micropores and formed adhesive bridges between soil grains, reducing detachment under stress.

These findings align with the conclusions of Ijimdiya and Akinwumi (2023), who emphasized the sustainable potential of starch-based stabilizers in road construction. Their study detailed how starch modification improved matrix cohesion and reduced the vulnerability of soils to moisture-induced degradation. The biopolymer not only enhanced inter-particle bonding but also helped form a film-like matrix around soil aggregates, reducing permeability and mitigating swell-shrink behavior under fluctuating moisture regimes. Collectively, these studies support the growing consensus that starch-based stabilizers, particularly those derived from cassava, offer a low-cost, eco-friendly alternative to conventional soil stabilizers. In regions like sub-Saharan Africa, where cassava is readily available and agricultural waste disposal remains a concern, the use of cassava starch for soil improvement aligns with circular economy principles and offers considerable benefits in terms of sustainability, performance, and accessibility for infrastructure development.

Despite these advances, most studies on cassava starch stabilization have been largely empirical, focusing on laboratory-based strength evaluations and moisture resistance without incorporating robust statistical modeling frameworks for predictive assessment and optimization. This limits the generalizability and scalability of findings, especially for field applications where variable interactions and trade-offs among multiple components must be quantitatively understood. The adoption of mixture design methodologies and regression-based modeling, such as the Scheffé's regression model, offers a powerful statistical approach for analyzing the influence of component proportions on performance outcomes in multicomponent systems (Montgomery, 2019).

Scheffé's model is specifically tailored for mixture experiments, where the response variable depends not on the absolute quantity of each component, but on their relative proportions within a fixed-sum constraint (typically summing to 1.0 or 100%). This property makes it ideal for modeling the strength, workability, and durability behavior of soil mixtures treated with varying proportions of binders such as cassava starch, cement, lime, or water (Cornell, 2011). The Scheffé quadratic or special cubic models provide flexible frameworks for capturing linear and interactive effects among components, allowing for the development of statistically validated predictive equations.

Empirical applications of Scheffé's mixture design in geotechnical engineering have demonstrated its capability to accurately model performance indices such as unconfined compressive strength (UCS), California Bearing Ratio (CBR), split tensile strength, and durability of stabilized soil blends. For instance, Eyo *et al.,* (2021) applied a (3,2) Scheffé simplex lattice design to model the UCS of soil blends incorporating lime, laterite, and water. The regression model demonstrated strong statistical significance ($p < 0.05$) and was validated with high coefficients of determination ($R^2 > 0.95$), confirming its predictive reliability.

Similarly, Osinubi and Eberemu (2019) used Scheffé's model to evaluate the interaction between cement, fly ash, and black cotton soil for the optimization of compressive strength and volumetric stability. Their study emphasized that mixture design methods allow not only for prediction but also for optimization of mix proportions that yield maximum or minimum response values, depending on design objectives. In the context of cassava starch stabilization, where optimal dosage must balance strength gain and cost-efficiency, this type of modeling is particularly beneficial.

Moreover, recent work by Adebisi et al. (2022) incorporated Scheffé's design to assess the strength performance of biopolymer–lateritic soil mixtures, illustrating that the model successfully identified significant component interactions and predicted peak strength values with minimal experimental runs. This supports the case for extending the use of Scheffé-based regression modeling to cassava starch–stabilized soils, thereby moving beyond trial-and-error approaches toward data-driven optimization and mechanistic understanding of stabilization behavior.

The use of Scheffé's regression in this context provides a structured methodology for optimizing the proportions of cassava starch, water, and soil to predict durability metrics such as UCS retention under wet–dry cycles. This statistical approach enables engineers and researchers to move beyond trial-and-error methods and toward predictive, optimized, and reproducible mix designs. Moreover, it aligns with the broader sustainability goals of reducing the environmental footprint of construction activities, promoting local materials, and enhancing the resilience of road infrastructure under climate variability.

This study, therefore, aims to assess the durability of cassava starch-stabilized lateritic soils using the Scheffé's regression model, providing a predictive framework that supports sustainable soil stabilization practices. The study integrates laboratory evaluation with statistical modeling to deliver both empirical and analytical insights into the stabilization potential of cassava starch, thus contributing to the growing body of knowledge on bio-based soil treatment alternatives.

2. MATERIALS AND METHODS

2.1 Materials

1. Lateritic Soil

The lateritic soil sample employed in this study was obtained from a borrow pit located in Choba, Port Harcourt, Nigeria (4.893510°N, 6.910277°E). The collected soil was sieved to retain particles passing through a 4.5 mm mesh to ensure uniformity and suitability for laboratory testing consistent with engineering standards. Chemical characterization revealed a silica to sesquioxide ratio ($SiO_2/(Al_2O_3 + Fe_2O_3)$) of 1.78, falling within the range of 1.33 to 2.00 as stipulated by Akije (2015), confirming its lateritic nature. The soil's calcium oxide (CaO) content was determined to be 0.408%, indicative of negligible natural cementing properties.

Atterberg limit tests showed a liquid limit of 29%, a plastic limit of 13.04%, and a plasticity index of 15.96%, classifying the soil as moderately plastic, characteristic of tropical lateritic soils. Particle size distribution analysis indicated a predominance of fine-grained material, with gravel content at 5%, sand fraction at 90% (comprising 30% medium sand, 25% coarse sand, and 35% fine sand), and silt at 15%. The gradation reflects a well-distributed sandy texture, conducive to compaction and permeability. The specific gravity was measured at 2.58, slightly below but within the typical range of 2.60–2.90 for fine-grained soils (Murthy, 2012).

Standard Proctor compaction tests yielded an optimum moisture content of 14.5% and a maximum dry density of 1.84 g/cm³, indicating moderate compaction characteristics appropriate for subgrade and subbase construction applications, particularly following stabilization treatments. These physicochemical and geotechnical properties affirm the soil's classification as lateritic and its suitability for stabilization studies.

2. Cassava Starch

Cassava starch, a naturally occurring polysaccharide made up of glucose units, was utilized in this study as the primary soil stabilizer. Commonly used as a thickening agent in culinary applications and also consumed as a staple food in many regions of Nigeria, the cassava starch was locally sourced from a market in Choba, Port Harcourt, Rivers State, where it was sold in traditional "paint rubber" containers. Its selection for this study is based on its biodegradability, which ensures minimal environmental impact, and its natural adhesive properties, which enhance interparticle bonding in soils. These characteristics make cassava starch a promising and sustainable alternative to conventional chemical stabilizers in geotechnical applications.

2.1 Water

Deionized water with a neutral pH of approximately 6.9, free from deleterious substances, was used throughout the experimental program. The water was sourced from the Geotechnical Laboratory of the Department of Civil and Environmental Engineering, University of Port Harcourt, ensuring consistency and reliability in hydration reactions during soil stabilization

2.2 Methods

The methodology adopted in this study comprised the development of a simplex lattice mixture design specifically structured for cassava starch-stabilized lateritic soil. Stabilized soil samples were prepared using varying proportions of cassava starch, and their mechanical performance was assessed through unconfined compressive strength (UCS) and indirect tensile strength (ITS) tests after a 28-day curing period. To evaluate durability, UCS and ITS retention tests were conducted following 12 cycles of wet–dry conditioning. Furthermore, Scheffé's regression models were formulated to predict the durability parameters of the stabilized soil. The validity and reliability of these models were confirmed using F-statistics for significance testing and coefficients of determination (R^2) for model accuracy.

2.2.1 Simplex Lattice Design

The simplex lattice mixture design method was employed to develop the mix proportions for cassava starch-stabilized lateritic soil. Following the approach described by Oguaghamba and Mama (2018), the design is characterized by a (q,m) configuration, where q represents the number of mixture components and m denotes the polynomial degree, corresponding to the maximum level of interaction among components. This framework establishes the simplex coordinate system, X_i, and enables the determination of the total number of required design points, N, within the experimental domain, as expressed mathematically in Equation (1) and Equation (2), respectively.

$$X_i = 0, \frac{1}{m}, \frac{2}{m}, \ldots \ldots .1 \qquad (1)$$

$$N = \frac{(q+m-1)!}{m!(q-1)!} \qquad (2)$$

In this study, a (3,2) simplex lattice mixture design was adopted, where the number 3 corresponds to the three components involved in the cassava starch-stabilized lateritic soil mixture, and 2 represents the assumed maximum degree of component interaction. In accordance with Equations (1) and (2), the resulting simplex coordinate values (Xi) are 0, ½, and 1, while the total number of design points (N) is 6. This value of N signifies the minimum number of experimental runs required to establish a statistically valid regression model for the system.

As prescribed by Scheffé's mixture theory, the component proportions are expressed using pseudo components, theoretical ratios that sum to unity. In the simplex coordinate system, each pure component occupies a vertex of the triangular design space, as shown in Figure 1. A fundamental constraint of the mixture model is that the sum of the pseudo mix ratios at any given point within the simplex must equal 1, which is mathematically represented as;

$$X_1 + X_2 + X_3 = 1 \quad (3)$$

Where, X_1, X_2, and X_3, are the pseudo proportions of the individual components (e.g., lateritic soil, cassava starch, and water-to-solids ratio) in the mixture design.

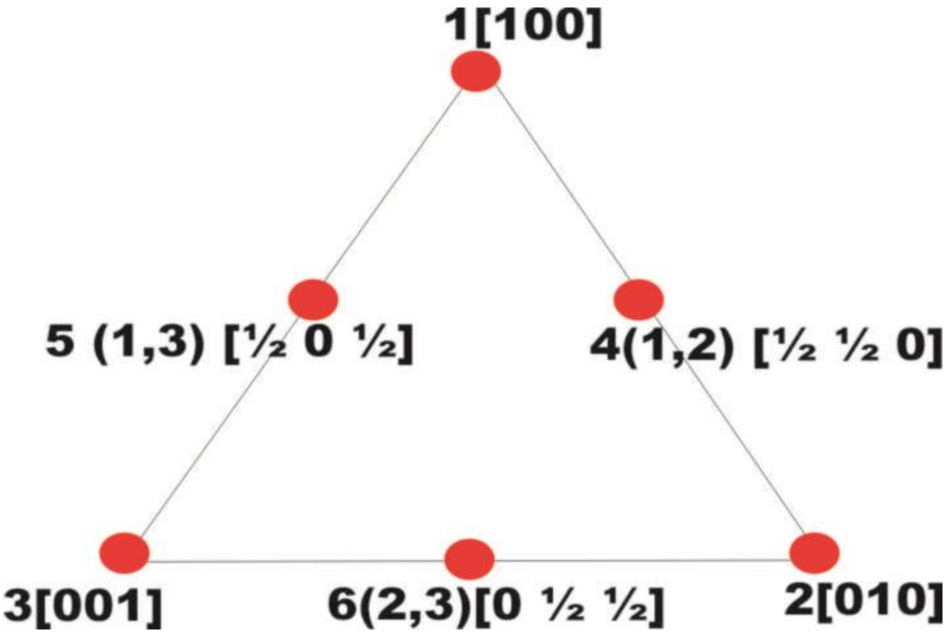

Figure 1: (3, 2) Simplex Lattice Structure

To satisfy the constraint defined in Equation (3), where the sum of the pseudo mix ratios equals unity, it is essential to convert the actual mix ratios into pseudo mix ratios. This transformation ensures that the mixture design adheres to the principles of the simplex lattice approach. The relationship between the actual component proportions and their corresponding pseudo mix ratios is expressed mathematically as follows;

$$Z = [A]X \quad (4)$$

Where:
Z = column matrix of real component ratio.
X = column matrix of pseudo component ratio.
[A]= coefficient matrix which is the transpose of the permutation matrix

In constructing the mix design table for the stabilization of lateritic soil, the permutation matrix [P] presented in Equation (5) was developed based on insights from relevant literature on cassava starch stabilization, alongside findings from preliminary laboratory tests. Cassava starch (CS) was incorporated at proportions ranging from 0% to 10% by mass of the lateritic soil, resulting in corresponding reductions in soil content from 100% to 90%. The water-to-solid (W/S) ratio was similarly constrained within the range of 12% to 16%, reflecting the observed effect of cassava starch on the soil's moisture demand. This range was deliberately selected with reference to the optimum moisture content (OMC) of 14.5% identified for the untreated lateritic soil.

The selected parameter bounds were then used to generate the permutation matrix [P], which outlines the actual mix proportions applied at the simplex vertices (Figure 1). Specifically, the vertices were defined by the coordinate sets (0.90; 0.10; 0.12), (0.95; 0.05; 0.14), and (1.00; 0.00; 0.16), corresponding to the proportions of lateritic soil, cassava starch, and the water-to-solid ratio, respectively. These combinations represent the extreme points of the mixture domain and collectively form the permutation matrix [P] used in the experimental design.

$$[P] = \begin{bmatrix} 0.900 & 0.100 & 0.120 \\ 0.950 & 0.050 & 0.140 \\ 1.000 & 0.000 & 0.160 \end{bmatrix} \quad (5)$$

With the corresponding pseudo mix components being;

$$[X] = \begin{bmatrix} 1.000 & 0.000 & 0.000 \\ 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 1.000 \end{bmatrix} \quad (6)$$

The transpose of [P] becomes the coefficient matrix [A] as shown in Equation (7)

$$[A] = \begin{bmatrix} 0.900 & 0.950 & 1.000 \\ 0.100 & 0.050 & 0.000 \\ 0.120 & 0.140 & 0.160 \end{bmatrix} \quad (7)$$

Using Equation (4), the pseudo component values were transformed into their corresponding actual (real) mixture proportions, as presented in Table 1. This conversion yielded a total of six (6) experimental runs designated for the trial mix investigations. To facilitate model validation, an additional six (6) control mix designs were generated, ensuring that each design point satisfied the fundamental constraint of ∑Xi =1. As a result, the experimental program comprised a total of twelve (12) distinct mix designs, six allocated for model development and six reserved for validation purposes.

The first six mix designs were employed in the formulation of the Scheffé regression models, capturing the relationship between component proportions and response variables. The remaining six designs were used exclusively for validating the predictive performance and robustness of the developed model, ensuring statistical reliability and consistency of the mixture design framework.

Table 1: Design Matrix for Trial Mixes of Cassava Stabilized soil components

N	Mix Proportions					
	Pseudo Proportions			Actual proportions		
	X_1	X_2	X_3	Z_1	Z_2	Z_3
1	1	0	0	0.90	0.10	0.12
2	0	1	0	0.95	0.05	0.14
3	0	0	1	1.00	0.00	0.16
4	0.5	0.5	0	0. 925	0.075	0.13
5	0.5	0	0.5	0.950	0.050	0.140
6	0	0.5	0.5	0.975	0.025	0.150

Where; Z_1= lateritic soil; Z_2 = Cassava starch; Z_3= w/s

Table 2: Design Matrix for Control Mixes of Cassava Stabilized soil components

N	Mix Proportions					
	Pseudo Proportions			Actual proportions		
	X_1	X_2	X_3	Z_1	Z_2	Z_3
1	0.4	0.4	0.2	0.940	0.060	0.136
2	0.3	0.3	0.4	0.955	0.045	0.142
3	0.2	0.2	0.6	0.970	0.030	0.148
4	0.1	0.6	0.3	0. 960	0.040	0.144
5	0.4	0.3	0.3	0.945	0.055	0.138
6	0.5	0.3	0.2	0.935	0.065	0.134

Where; Z_1= lateritic soil; Z_2 = Cassava starch; Z_3= w/s

2.2.2 Cassava Starch Stabilized Lateritic Soil Sample Preparation

Lateritic soil samples stabilized with cassava starch were proportioned by weight and mixed manually, then compacted following the ASTM D698 (2015) standard. All samples underwent membrane curing for a duration of 28 days prior to testing and durability evaluation. For each experimental run, two samples were prepared in accordance with the established experimental design. The stabilization procedure is illustrated in Figure 2.

a. Cassava starch **b. Lateritic soil** **c. Cassava starch-soil**

Figure 2: Flow of the Stabilization Process

2.2.3 Unconfined Compressive Strength (UCS) Test

The UCS of cassava stabilized lateritic soils was determined in accordance to ASTM D2166 (2016) in order to obtain the compressive stress of cassava starch stabilized lateritic soil samples. During this analysis, 100mm × 200mm cylindrical molds were used. Cassava starch based treated soil samples were loaded and the failure load recorded. The UCS was then evaluated using Equation (8).

$$\sigma_u = \frac{P\ (in\ N)}{A\ (in\ mm^2)} \quad (8)$$

Where, P is the failure load and A is the cross-sectional area of the tested corn starch based stabilized lateritic soil.

2.2.4 Indirect Tensile Strength (ITS) Test

The indirect tensile strength in this study was measured using the split cylinder test, conducted in accordance with ASTM C496 (2011). A 50mm × 100mm cylindrical steel mold was used for the test. The indirect tensile strength was subsequently calculated using Equation (9).

$$\sigma_t = \frac{2P}{\pi D t} \quad (9)$$

Where; P is the tensile failure load, D is the diameter or width of soil specimen and t represents the thickness

2.2.5 Durability Assessment of Cassava Starch Stabilized Lateritic Soil

The durability performance of the cassava starch-stabilized lateritic soil was evaluated through both Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) retention following standardized wet–dry cycling procedures. These assessments were carried out in accordance with ASTM D2166 (2016) for UCS and ASTM D6931 for ITS.

All stabilized specimens were subjected to 12 wet–dry cycles to simulate environmental exposure conditions. Each cycle consisted of 5 hours of water immersion, followed by 16 hours of oven drying at 60°C. This cyclic process was designed to assess the material's resistance to degradation caused by moisture fluctuations and drying stresses, conditions commonly encountered in tropical and sub-tropical geotechnical applications.

At the end of the 12th cycle, both UCS and ITS tests were performed on the conditioned specimens. The durability of the stabilized soil was quantified by calculating the UCS retention and ITS retention, defined as the ratio of strength after the 12th cycle to the initial strength before the commencement of the cycles, expressed using Equations (9) and (10) respectively:

$$UCS_{retention} = \frac{UCS_{final}}{UCS_{initial}} X\ 100 \quad (9)$$

$$ITS_{retention} = \frac{ITS_{final}}{ITS_{initial}} X\ 100 \quad (10)$$

Where;
UCS_{final} is the UCS after the 12th cycle,
$UCS_{initial}$ is the UCS before the start of the wet-dry cycles,
ITS_{final} is the ITS after the 12^{th} cycle, and,
$ITS_{initial}$ is the ITS before the start of the wet-dry cycles

2.2.6 Scheffe's Regression Model Formulation

According to Scheffe (1958), mixture proportions are being represented in pseudo (theoretical) mix ratios. The (q, m) polynomial have a general form represented by Equation (11) (Scheffe, 1958);

$$Y = b_o + \Sigma b_i x_i + \Sigma b_{ij} x_i x_j + \Sigma b_{ijk} x_i x_j x_k + \cdots + \Sigma b_{i1,i2..im} x_{i1} x_{i2} x_{im} \quad (11)$$

Where; $1 \le i \le q$, $1 \le i \le j \le q$, $1 \le i \le j \le k \le q$; b_o is a constant coefficient
For (3, 2) polynomial problem as adopted in this study, Equation (11) becomes;

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 \quad (12)$$

Multiplying through Equation (3) by constant b_0, yields Equation (13).

$$b_0 X_1 + b_0 X_2 + b_0 X_3 = b_0 \quad (13)$$

Again, multiplying Equation (3) by X_1, X_2, and X_3 in succession and rearranging, Equation (14) is produced.

$$\begin{Bmatrix} X_1^2 = X_1 - X_1 X_2 - X_1 X_3 \\ X_2^2 = X_2 - X_1 X_2 - X_2 X_3 \\ X_3^2 = X_3 - X_1 X_3 - X_2 X_3 \end{Bmatrix} \quad (14)$$

Substituting Equations (12) and (13) into Equation (12), Equation (15) was obtained after necessary transformation.

$$Y = (b_0 + b_1 + b_{11}) X_1 + (b_0 + b_2 + b_{22}) X_2 + (b_0 + b_3 + b_{33}) X_3 + (b_{12} - b_{11} - b_{22}) X_1 X_2 + (b_{13} - b_{11} - b_{33}) X_1 X_3 + (b_{23} - b_{22} - b_{33}) X_2 X_3 \quad (15)$$

Denoting; $\beta_i = b_0 + b_i + b_{ii}$ and
$\beta_{ij} = b_{ij} - b_{ii} - b_{jj}$

The reduced second degree polynomial in 3 variables is shown by Equation (16).

$$Y = \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_{12}X_1X_3 + \beta_{13}X_1X_3 + \beta_{23}X_2X_3 \quad (16)$$

The number of coefficients has reduced from 10 in Equation (12) to 6 in Equation (16). Thus, the reduced second degree polynomial in q-variables is as shown by Equation (17).

$$Y = \sum_{1\le i\le q} \beta_i X_i + \sum_{i\le j\le q} \beta_{ij} X_iX_j \quad (17)$$

Where;
Y = Expected response
β_i, β_{ij} = Coefficients of the quadratic polynomial
X_i, X_j = Pseudo proportion of factors considered

Substituting the vertices coordinates of Figure 1 into Equation (16) yields Equation (18)

$$\begin{Bmatrix} Y_1 = \beta_1 \\ Y_2 = \beta_2 \\ Y_3 = \beta_3 \end{Bmatrix} \quad (18)$$

From Figure 3.1, Point X_{12}, Equation (19) can be deduced;

$$Y_{12} = \frac{1}{2}X_1 + \frac{1}{2}X_2 + \frac{1}{4}X_1X_2 \quad (19)$$

$$= \frac{1}{2}\beta_1 + \frac{1}{2}\beta_2 + \frac{1}{4}\beta_{12}$$

$\beta_i = Y_i$, where i = 1, 2, 3,……..n. Then substituting into Equation (19) yields:

$$Y_{12} = (½)Y_1 + (½)Y_2 + (¼)\beta_{12} \quad (20)$$

Simplifying Equation (20), yields:

$$\beta_{12} = 4Y_{12} - 2Y_1 - 2Y_2 \quad (21)$$

Similarly, Equation (22) to Equation (24) can be developed. Thus:

$$\left.\begin{matrix} \beta_{13} = 4Y_{13} - 2Y_1 - 2Y_3 & (22) \\ \beta_{12} = 4Y_{12} - 2Y_1 - 2Y_2 & (23) \\ \beta_{23} = 4Y_{23} - 2Y_2 - 2Y_3 & (24) \end{matrix}\right\}$$

By generalizing, Equations (18) to (24), Equation (25) was formed.

$$\beta_i = Y_i$$
$$\beta_{ij} = 4Y_{ij} - 2Y_i - 2Y_j \quad (25)$$

Equation (25) presents the formula for estimating the coefficients of the (3, 2) second degree polynomial in Equation (16).

2.2.7 Model Validation and Verification

The adequacy of the developed Scheffé models was evaluated using the Fisher test (F-test). This statistical test involves calculating the F-statistic, which represents the ratio of the variance between the model's predicted responses and the actual experimental results.

The hypotheses for validation were:

Null Hypothesis (H_0): No significant difference exists between experimental and predicted responses.
Alternate Hypothesis (H_1): A significant difference exists between experimental and predicted responses.
The F-test was conducted using the formula:

$$F = \frac{S_1^2}{S_2^2} \quad (26)$$

Where; S_1^2 = Larger of both variances, S_2^2 = Smaller of both variances, calculated as:

$$S^2 = \frac{1}{n-1}\left[\sum(Y - \bar{Y})^2\right] \quad (27)$$

The models are deemed adequate when the calculated F-value is less than the critical value obtained from the F-distribution table. At a 5% significance level and 5 degrees of freedom, the critical F-value is 5.05. If the computed F-value falls below this threshold, the null hypothesis is accepted, indicating that the model sufficiently fits the data. Conversely, if the F-value exceeds 5.05, the alternate hypothesis is accepted, suggesting that the model is not statistically adequate.

In another vane, developed models were also subjected to R^2 statistics for verification testing. The R^2 values were calculated in accordance to Equation (28).

$$R^2 = \frac{\Sigma(y_{est} - \bar{y})^2}{\Sigma(y - \bar{y})^2} \quad (28)$$

Where;
y_{est} = model or estimated value,
y = experimental value and
$\bar{y}$ = mean experimental value

3. RESULTS AND DISCUSSION

3.1 Strength Retention of Cassava Starch Stabilized Lateritic Soil under Wet–Dry Cycles

The durability performance of cassava starch-stabilized lateritic soil was assessed in terms of both Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) retention following 12 wet–dry cycles. The results, presented in Tables 3 and 4, highlight the variations in strength retention across different trial mixes.

For UCS retention, values ranged from 69.68% in trial mix 3 to 91.24% in trial mix 4. Initially, before wet–dry conditioning, UCS values spanned from 828.77 kPa in trial mix 3 to 1342.08 kPa in trial mix 4. After the 12 wet–dry cycles, the UCS values reduced to 577.47 kPa and 1224.44 kPa, respectively, indicating varying degrees of resistance to moisture-induced degradation.

Similarly, ITS retention ranged from 71.79% in trial mix 3 to 92.91% in trial mix 4. The initial ITS values prior to cycling were between 417.06 kPa (trial mix 3) and 679.06 kPa (trial mix 4). Post-cycling values dropped to 299.43 kPa and 630.94 kPa, respectively.

According to ASTM D559/D559M-15 (Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures), a UCS retention value of at least 80% is considered acceptable for durable stabilization treatments (ASTM International, 2015). Therefore, while Mix 3 slightly under-performs, Mix 4 not only meets but exceeds the durability threshold, confirming cassava starch's effectiveness as a soil stabilizer under cyclic environmental loading. Similarly, Amu *et al.,* (2020) reported that natural polymers, including cassava-based binders, improved the wet–dry resistance of lateritic soil mixtures, achieving UCS retention values above 85%. Their findings also demonstrated that the use of bio-stabilizers led to the formation of water-resistant gels within the soil matrix, contributing to improved cohesion and reduced pore water ingress. Additionally, the Nigerian General Specifications for Roads and Bridges recommend a minimum UCS of 687 kPa for subgrade applications (Federal Ministry of Works, 2013). Trial Mix 4 not only meets this requirement post-conditioning but retains strength well above this threshold, indicating the potential of cassava starch for sustainable subgrade stabilization.

The AASHTO T 283 standard stipulates that for moisture susceptibility testing of asphalt-stabilized or chemically stabilized soils, a indirect tensile strength retention above 70% is considered acceptable for durability (AASHTO, 2020). Based on this benchmark, all trial mixes in the present study meet or exceed the threshold, with Trial Mix 4 performing especially well. Comparable outcomes were reported by Nnochiri and Edeh (2021), who found that bio-stabilized lateritic soils, when subjected to moisture conditioning, maintained tensile strength retention above 85%. Their study emphasized that the improved microstructural interactions induced by bio-polymers like starch increased particle bonding and reduced void ratios, ultimately enhancing resistance to tensile failure.

Table 3: UCS Retention Results for Cassava Starch Stabilized Lateritic Soil (Trial Mixes)

N	Mix Proportions						Before wet-dry cycles		After the 12th cycle		Response Symbol	UCS retention (%)
	Pseudo Proportions			Actual proportions								
	X_1	X_2	X_3	Z_1	Z_2	Z_3	Failure Comp. load (kN)	$UCS_{initial}$ (kPa)	Failure Comp. load	UCS_{final} (kPa)		
1	1	0	0	0.9	0.1	0.12	7.56	962.44	6.38	812.73	Y_1	84.44
2	0	1	0	0.95	0.05	0.14	9.07	1154.93	8.02	1021.26	Y_2	88.43
3	0	0	1	1	0	0.16	6.51	828.77	4.54	577.47	Y_3	69.68
4	0.5	0.5	0	0. 925	0.075	0.13	10.54	1342.08	9.62	1224.44	Y_{12}	91.24
5	0.5	0	0.5	0.95	0.05	0.14	9.07	1154.93	8.02	1021.26	Y_{13}	88.43
6	0	0.5	0.5	0.975	0.025	0.15	7.48	951.75	5.92	753.91	Y_{23}	79.21

Where; X1, Z_1= pseudo and actual lateritic soil proportion; X2, Z_2 = pseudo and actual cassava starch proportion; X3, Z_3= pseudo and actual w/s proportion

Table 4: ITS Retention Results for Cassava Starch Stabilized Lateritic Soil (Trial Mixes)

N	Mix Proportions						Before wet-dry cycles		After the 12th cycle		Response Symbol	ITS retention (%)
	Pseudo Proportions			Actual proportions								
	X_1	X_2	X_3	Z_1	Z_2	Z_3	Failure Comp. load (kN)	$ITS_{initial}$ (kPa)	Failure Comp. load	ITS_{final} (kPa)		
1	1	0	0	0.9	0.1	0.12	4.28	545.39	3.53	449.14	Y1	82.35
2	0	1	0	0.95	0.05	0.14	4.75	604.20	4.28	545.39	Y2	90.27

3	0	0	1	1	0	0.16	3.28	417.06	2.35	299.43	Y3	71.79
4	0.5	0.5	0	0. 925	0.075	0.13	5.33	679.06	4.96	630.94	Y12	92.91
5	0.5	0	0.5	0.95	0.05	0.14	4.75	604.20	4.28	545.39	Y13	90.27
6	0	0.5	0.5	0.975	0.025	0.15	3.95	502.61	3.19	406.37	Y23	80.85

Where; X1, Z_1= pseudo and actual lateritic soil proportion; X2, Z_2 = pseudo and actual cassava starch proportion; X3, Z_3= pseudo and actual w/s proportion

3.2 Scheffe's Regression Model for Predicting the UCS Retention of Cassava Starch Stabilized Lateritic Soil

Table 3 presents the UCS retention of cassava starch stabilized lateritic soil for trial mixes. With the aid of Table 3 in conjunction with Equation (25), the model coefficients of the Scheffe's (3, 2) regression model for predicting the UCS retention of cassava starch stabilized lateritic soil is thus obtained;

$\beta_1 = Y_1 = 84.44$
$\beta_2 = Y_2 = 88.43$
$\beta_3 = Y_3 = 69.68$
$\beta_{12} = 4Y_{12} - 2Y_1 - 2Y_2 = 4(91.24) - 2(84.44) - 2(88.43) = 19.22$
$\beta_{13} = 4Y_{13} - 2Y_1 - 2Y_3 = 4(88.43) - 2(84.44) - 2(69.68) = 45.48$
$\beta_{23} = 4Y_{23} - 2Y_2 - 2Y_3 = 4(79.21) - 2(88.43) - 2(69.68) = 0.62$

Substituting the above coefficient values into Equation (16), the optimization model for predicting the UCS retention of cassava starch stabilized lateritic soil becomes;

$$UCS_{retention} = 84.44X_1 + 88.43X_2 + 69.68X_3 + 19.22X_1X_2 + 45.48X_1X_3 + 0.62X_2X_3 \quad (29)$$

Where; X_1 represents the pseudo proportion of the lateritic soil in the stabilized soil
X_2 represents the pseudo proportion of the cassava starch in the stabilized soil
X_3 represents the pseudo proportion of the water/solids ratio in the stabilized soil

As shown in Table 5, the model validation was performed using F-Statistics, a statistical technique for evaluating whether a predictive model significantly explains variability in the response variable. The calculated F-value of 1.016 was compared with the critical F-value of 5.05 at a 5% significance level and 5 degrees of freedom. Since the calculated F-value is less than the critical value, the null hypothesis (H_0), which assumes that the regression model adequately fits the data, is not rejected. This implies that there is no significant evidence to suggest that the model is unfit for predicting UCS retention in cassava starch-treated soils.

Further supporting the model's reliability is the coefficient of determination (R^2), depicted in Figure 3, with a reported value of 99.85%. This value indicates that the regression model explains over 99% of the variability in UCS retention within the design space, a remarkably high degree of predictive accuracy. A high R^2 value, particularly above 90%, is generally regarded as strong evidence of model adequacy in engineering and geotechnical research (Dai *et al.,* 2022).

Table 5: F-Statistics for the Validation of Scheffe's Model for Predicting UCS retention of Cassava Starch Stabilized Lateritic Soil

S/N	UCSretention Experimental Value (Control Mix) =Y_e	UCSretention Predicted or Model Value= Ym	Y_e-$\hat{Y}_e$	Ym-$\hat{Y}$m	$(Y_e-\hat{Y}_e)^2$	$(Ym-\hat{Y}m)^2$
1	90.01	89.847	2.662	2.557	7.08447	6.53757
2	86.96	86.995	-0.388	-0.296	0.15080	0.08734
3	82.71	82.683	-4.638	-4.608	21.51414	21.22936
4	85.28	85.035	-2.068	-2.255	4.27800	5.08563
5	89.01	89.029	1.662	1.738	2.76114	3.02227
6	90.12	90.153	2.772	2.863	7.68214	8.19601
	$\hat{Y}_e$ = 87.348	$\hat{Y}$m = 87.290			∑= 43.471	∑= 44.158
Square of deviation of experimental UCSretention values from mean UCSretention value				S_e^2	5.434	
Square of deviation of predicted UCSretention values from mean UCSretention value				Sm^2	5.520	
F- Calculated value, ratio of the two deviations, **F-cal**					**1.016**	

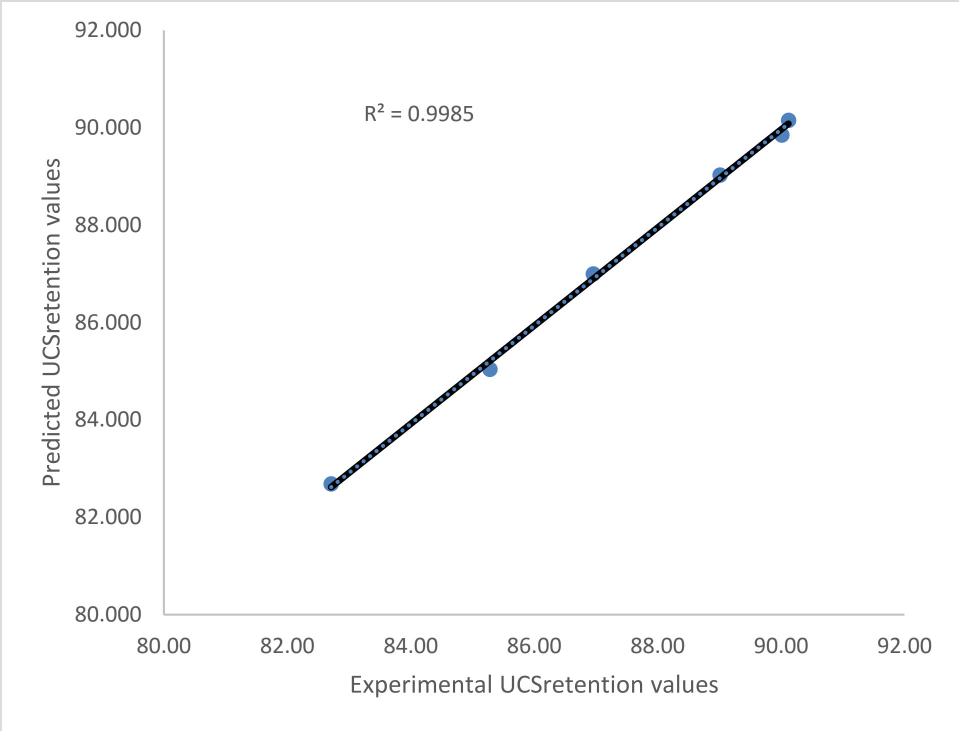

Figure 3: Predicted Vs Experimental UCS retention for Cassava Starch Stabilized Soil

3.3 Scheffe's Regression Model for Predicting the ITS Retention of Cassava Starch Stabilized Lateritic Soil

Table 4 presents the ITS retention of cassava starch stabilized lateritic soil for trial mixes. With the aid of Table 4 in conjunction with Equation (25), the model coefficients of the Scheffe's (3, 2) optimization models for predicting the ITS retention of cassava starch stabilized lateritic soil is thus obtained;

$\beta_1 = Y_1 = 82.35$
$\beta_2 = Y_2 = 90.27$
$\beta_3 = Y_3 = 71.79$
$\beta_{12} = 4Y_{12} - 2Y_1 - 2Y_2 = 4(91.91) - 2(82.35) - 2(90.27) = 22.40$
$\beta_{13} = 4Y_{13} - 2Y_1 - 2Y_3 = 4(90.27) - 2(82.35) - 2(71.79) = 52.80$
$\beta_{23} = 4Y_{23} - 2Y_2 - 2Y_3 = 4(80.85) - 2(90.27) - 2(71.79) = -0.72$

Substituting the above coefficient values into Equation (16), the optimization model for predicting the ITS retention of cassava starch stabilized lateritic soil becomes;

$$ITS_{retention} = 82.35X_1 + 90.27X_2 + 71.79X_3 + 22.40X_1X_2 + 52.80X_1X_3 - 0.72X_2X_3 \qquad (30)$$

Where; X_1 represents the pseudo proportion of the lateritic soil in the stabilized soil
X_2 represents the pseudo proportion of the cassava starch in the stabilized soil
X_3 represents the pseudo proportion of the water/solids ratio in the stabilized soil

Table 6 presents the ANOVA-based validation of the model, with a calculated F-value of 1.129 compared to the critical F-value of 5.05 at a 5% significance level and 5 degrees of freedom. Since the F-calculated is substantially lower than the F-critical, the null hypothesis (H_0) is retained. This statistical outcome confirms that the regression model is statistically reliable and does not significantly deviate from the actual data points, thus validating its application for predicting ITS retention in the tested soil system.

This approach is consistent with modeling principles outlined in Montgomery (2020), who emphasized that a lower F-ratio than the critical value at a given confidence level indicates model adequacy, especially in designed experiments such as mixture or factorial designs. Further verification of the model's predictive performance is illustrated in Figure 4, which displays a coefficient of determination (R^2) of 99.57%. This implies that the model can explain more than 99% of the variability in the ITS retention data, indicating an exceptionally high level of accuracy. According to Dai *et al.,* (2022), R^2 values exceeding 90% are considered highly satisfactory in predictive soil models, especially when modeling mechanical behavior under durability test conditions. Comparable studies, such as those by

Akinwumi *et al.,* (2019), utilized regression models to predict strength characteristics of stabilized tropical soils and reported that R^2 values above 95% confirmed excellent model reliability. The R^2 of 99.57% in this study further reinforces the predictive power of the cassava starch-based model and validates its use for performance forecasting under wet–dry cyclic loading.

Table 6: F-Statistics for the Validation of Scheffe's Model for Predicting ITS retention of Cassava Starch Stabilized Lateritic Soil

S/N	ITSretention Experimental Value (Control Mix) =Y_e	ITSretention Predicted or Model Value= Ym	$Y_e-\hat{Y}_e$	Ym-Ŷm	$(Y_e-\hat{Y}_e)^2$	$(Ym-\hat{Y}m)^2$
1	90.37	90.453	2.757	2.860	7.59921	8.17884
2	87.64	87.287	0.027	-0.307	0.00071	0.09396
3	83.05	83.121	-4.563	-4.473	20.82401	20.00355
4	84.68	84.769	-2.933	-2.824	8.60444	7.97573
5	89.42	89.386	1.807	1.792	3.26404	3.21222
6	90.52	90.544	2.907	2.951	8.44871	8.70879
	$\hat{Y}_e = 87.613$	$\hat{Y}m = 87.593$			∑= 48.741	∑= 48.173
Square of deviation of experimental ITSretention values from mean ITSretention value				S_e^2	6.093	
Square of deviation of predicted ITSretention values from mean ITSretention value				Sm^2	6.022	
F- Calculated value, ratio of the two deviations, **F-cal**					**1.012**	

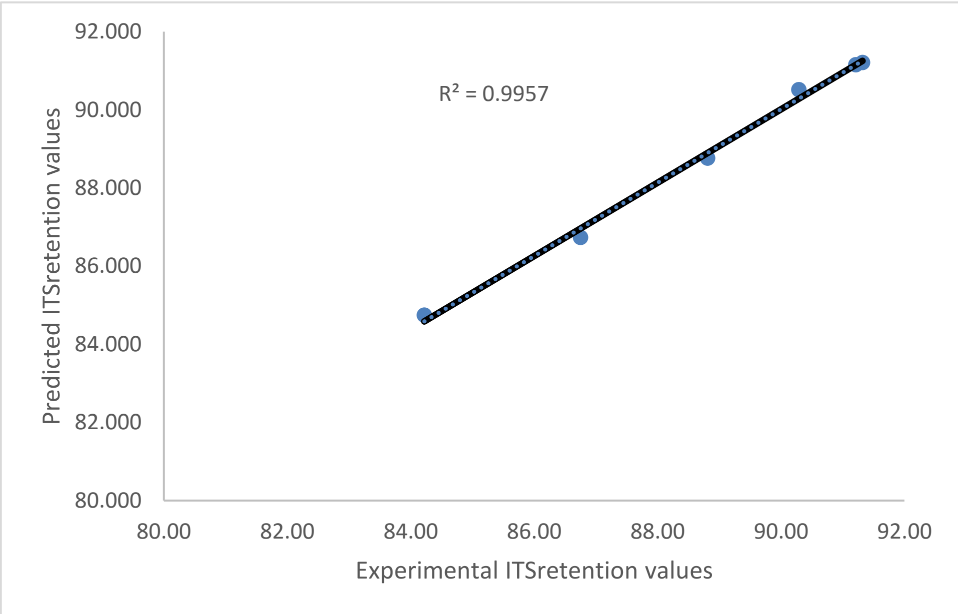

Figure 4: Predicted Vs Experimental ITS Retention for Cassava Starch Stabilized Soil

3. CONCLUSION

This study investigated the durability of cassava starch-stabilized lateritic soil under repeated wet–dry cycles, focusing on strength retention using Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) as performance indicators. The goal was to evaluate the stabilizing potential of cassava starch and to develop reliable predictive models using Scheffé's regression. Based on the experimental findings and statistical analysis, the following key conclusions were drawn;

i. Cassava starch significantly improved the durability of lateritic soil under wet–dry cycles. Trial Mix 4 showed the highest strength retention, with 91.24% UCS and 92.91% ITS. These values exceeded ASTM and AASHTO minimum durability standards. This confirms cassava starch's effectiveness as a moisture-resistant soil stabilizer.

ii. After 12 wet–dry cycles, Mix 4 maintained a UCS of 1224.44 kPa. This exceeds the 687 kPa minimum requirement for subgrades in Nigeria. It highlights cassava starch's suitability for tropical pavement applications. The stabilizer meets key geotechnical performance standards for road bases.

iii. The Scheffé (3,2) regression models developed for predicting UCS and ITS retention showed strong reliability. The F-values for both models were below the critical threshold, confirming good model fit. High R^2 values of 99.85% for UCS and 99.57% for ITS indicate excellent predictive accuracy. These results surpass the commonly accepted 90% benchmark in soil mechanics modeling, confirming the models' robustness

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