IJRP.ORG
International Journal of Research Publications
ISSN: 2708-3578 (Online)

MECHANICAL AND MICROSTRUCTURAL PERFORMANCE OF EXPANSIVE SOILS STABILIZED WITH FLY ASH–DESULPHOGYPSUM BLENDS

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ABSTRACT: Expansive soils pose significant challenges to civil engineering infrastructure due to their high plasticity, excessive swelling, and shrinkage behavior under fluctuating moisture conditions. These characteristics often lead to structural distress, including pavement cracking, foundation settlement, and loss of bearing capacity, particularly in regions such as the Niger Delta where seasonal moisture variation is pronounced . This study investigated the effectiveness of industrial waste materials, specifically fly ash and desulphogypsum, as sustainable stabilizing agents for improving the geotechnical properties of expansive soils. Laboratory experiments were conducted on untreated and treated soil samples with varying proportions of fly ash (5–15%) and desulphogypsum (5–15%), including their combined application. The natural soil was classified as highly plastic clay (CH) with a liquid limit of 92% and plasticity index of 71%, indicating high swelling potential. The addition of stabilizers significantly modified the soil behavior. The plasticity index decreased progressively with increasing stabilizer content, reaching a minimum value of 24% for the combined mix of 10% fly ash and 15% desulphogypsum. Compaction characteristics improved, with maximum dry density increasing from 1.485 g/cm³ to 1.556 g/cm³, while optimum moisture content reduced from 24.8% to 19.6%. Unconfined compressive strength (UCS) results demonstrated substantial improvement in strength due to stabilization. The untreated soil exhibited a UCS value of 89.2 kPa, which increased to 456.3 kPa after 28 days of curing for the combined stabilizer mix, representing a 411% increase. Regression models developed for predicting UCS and plasticity index reduction yielded strong correlations with coefficients of determination (R^2) of 0.887 and 0.862, respectively, and mean absolute error below 8%. Sensitivity analysis revealed that incremental increases in fly ash and desulphogypsum content contributed positively to strength development, with fly ash having a slightly higher influence. Optimization analysis identified an optimal stabilizer combination of 16.1% fly ash and 10.9% desulphogypsum, corresponding to a predicted UCS of 468.3 kPa and a minimum plasticity index of 22.1%. Economic evaluation showed that the combined stabilization method cost approximately ₦3,600/m³ compared to ₦11,700/m³ for conventional lime stabilization, resulting in a cost reduction of about 69%. The results demonstrated that the combined use of fly ash and desulphogypsum significantly improved the engineering performance of expansive soils by reducing plasticity, enhancing strength, and improving compaction characteristics. The study established that these industrial by-products offer a cost-effective and environmentally sustainable alternative for ground improvement in the Niger Delta, with strong potential for application in road construction and foundation engineering.

Keywords:
Expansive Soil, Soil Stabilization, Fly Ash, Desulphogypsum, Unconfined Compressive Strength, Plasticity Index, Compaction Characteristics, Maximum Dry Density, Optimum Moisture Content, Industrial Waste Utilization, Geotechnical Engineering, Soil Improvement, Regression Modeling, Optimization Analysis, Sustainable Construction.

1. INTRODUCTION

Expansive soils have long been recognized as one of the most problematic geomaterials in geotechnical engineering due to their significant volume change behavior when subjected to variations in moisture content. These soils exhibit swelling when wet and shrinkage when dry, leading to substantial ground movement that can adversely affect engineering structures such as buildings, pavements, and foundations (Chen, 1988; Nelson & Miller, 1992). The presence of expansive soils in many parts of the world, particularly in tropical and subtropical regions, has made their stabilization a critical concern in civil engineering practice. In the Niger Delta region of Nigeria, the problem is further compounded by high rainfall intensity, fluctuating groundwater levels, and poor drainage conditions, all of which contribute to the cyclic swelling and shrinkage of clayey soils .

The engineering behavior of expansive soils is largely governed by their mineralogical composition, particularly the presence of clay minerals such as montmorillonite, which have a high affinity for water (Holtz & Kovacs, 1981). These minerals possess a large specific surface area and a high capacity for water absorption, resulting in significant changes in soil volume and mechanical properties. As a result, structures founded on such soils often experience differential settlement, cracking, and eventual structural failure if proper ground improvement measures are not implemented. Previous studies have shown that the severity of damage caused by expansive soils is often underestimated during the design phase, leading to increased maintenance costs and reduced service life of infrastructure (Nelson et al., 2001).

In Nigeria, expansive soils are commonly encountered in regions with high clay content, including parts of the Niger Delta, where they pose serious challenges to road construction and foundation design. The natural soil investigated in this study was classified as highly plastic clay (CH) with a liquid limit of 92% and a plasticity index of 71%, indicating a high swelling potential . Such soils are generally unsuitable for engineering applications without stabilization, as their high plasticity leads to low shear strength and high compressibility. Consequently, there is a need for effective and sustainable methods of improving their engineering properties.

Soil stabilization has been widely adopted as a practical solution for improving the performance of expansive soils. Traditional stabilization methods involve the use of additives such as lime and cement, which enhance soil strength through chemical reactions that form cementitious compounds (Ingles & Metcalf, 1972). Lime stabilization, in particular, has been extensively used due to its effectiveness in reducing plasticity and increasing strength. However, the high cost of lime and cement, as well as their environmental impact in terms of carbon emissions, has necessitated the exploration of alternative materials for soil stabilization (Little, 1995).

In recent years, there has been growing interest in the use of industrial by-products and waste materials as stabilizing agents for soils. Materials such as fly ash, blast furnace slag, and gypsum derivatives have been investigated for their potential to improve soil properties while also addressing environmental concerns associated with waste disposal (Edil et al., 2006). Fly ash, a by-product of coal combustion, has been widely studied due to its pozzolanic properties, which enable it to react with calcium hydroxide in the presence of water to form cementitious compounds such as calcium silicate hydrate (C–S–H) (Mehta & Monteiro, 2006). These reactions contribute to increased soil strength and reduced plasticity.

Desulphogypsum, another industrial by-product, is generated during flue gas desulfurization processes in power plants. It contains significant amounts of calcium sulfate, which can participate in chemical reactions with soil and other additives to form compounds such as ettringite, thereby improving soil strength and stability (Derucher et al., 1999). The combined use of fly ash and desulphogypsum has been reported to produce synergistic effects, leading to enhanced stabilization performance compared to the use of either material alone.

Several studies have demonstrated the effectiveness of fly ash in improving the geotechnical properties of expansive soils. For instance, Prabakar et al. (2004) reported that the addition of fly ash significantly reduced the plasticity index and increased the unconfined compressive strength of expansive soils. Similarly, Pandian (2004) observed that fly ash stabilization improved compaction characteristics and reduced swelling potential. The effectiveness of gypsum-based materials in soil stabilization has also been documented, with studies showing that calcium sulfate contributes to the formation of cementitious bonds that enhance soil strength (Ghosh & Subbarao, 2007).

Despite the promising results obtained from previous studies, there remains a need to investigate the combined effect of fly ash and desulphogypsum under specific environmental and soil conditions, particularly in the Niger Delta region. The unique geotechnical characteristics of soils in this region, coupled with high moisture variability, necessitate localized studies to determine optimal stabilization strategies. Furthermore, there is a growing emphasis on sustainable construction practices, which has increased the demand for environmentally friendly and cost-effective stabilization methods.

The use of industrial waste materials for soil stabilization offers several advantages, including reduced material costs, conservation of natural resources, and mitigation of environmental pollution. By utilizing waste materials such as fly ash and desulphogypsum, it is possible to achieve both engineering and environmental benefits, thereby promoting sustainable development. In addition, the use of locally available materials can significantly reduce transportation costs and improve the feasibility of large-scale stabilization projects.

The present study therefore aimed to evaluate the effectiveness of fly ash and desulphogypsum in improving the engineering properties of expansive soils in the Niger Delta. The investigation focused on key parameters such as plasticity index, compaction characteristics, and unconfined compressive strength. The study also incorporated regression modeling and optimization techniques to predict soil behavior and determine optimal stabilizer proportions. This approach provided a more comprehensive understanding of the stabilization process and enabled the development of practical recommendations for field application.

Furthermore, the study included an economic analysis to assess the cost-effectiveness of the proposed stabilization method compared to conventional techniques such as lime stabilization. The results of this analysis were expected to provide valuable insights for decision-making in construction projects, particularly in regions where cost constraints are a major consideration.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this study consisted of expansive soil obtained from the Niger Delta region, fly ash, desulphogypsum, and potable water. The soil sample was collected from a location representative of subgrade conditions, where expansive soil behavior is commonly encountered in engineering practice. The sampling depth was selected to reflect the typical depth of influence for shallow foundations and pavement subgrades. The collected soil was carefully sealed in airtight containers immediately after sampling to preserve its natural moisture condition and prevent contamination.

Upon arrival at the laboratory, the soil was subjected to preliminary inspection and air-drying under controlled conditions. The air-drying process was carried out at room temperature to avoid alteration of the soil's mineralogical structure. After drying, the soil was gently pulverized using a wooden mallet to break down lumps without crushing individual particles. The pulverized soil was then passed through a 4.75 mm sieve to obtain a uniform sample suitable for laboratory testing.

Initial classification tests indicated that the soil exhibited characteristics of highly plastic clay, with a high liquid limit and plasticity index. These properties confirmed the expansive nature of the soil, making it a suitable candidate for stabilization studies. The high plasticity implied that the soil had a strong affinity for water and a tendency to undergo significant volume changes, which could adversely affect structural performance if not properly treated.

Fly ash used in this study was obtained from a thermal power generation facility. It was a fine, powdery material composed primarily of silica, alumina, and small amounts of calcium oxide. The particle size of fly ash was significantly smaller than that of soil particles, which allowed it to fill voids and improve packing density when mixed with soil. The pozzolanic nature of fly ash enabled it to react with available calcium in the presence of water to form cementitious compounds, thereby enhancing the strength and stability of the soil.

Desulphogypsum was sourced as an industrial by-product generated during flue gas desulfurization processes. It consisted mainly of calcium sulfate and was characterized by its fine texture and high purity. The presence of calcium in desulphogypsum made it suitable for use in soil stabilization, as it could participate in chemical reactions that improve the bonding between soil particles. When combined with fly ash, desulphogypsum contributed to the formation of stable compounds that enhanced the mechanical properties of the treated soil.

Potable water was used for all mixing and curing operations. The water was free from impurities such as organic matter, salts, and oils that could interfere with chemical reactions or affect the strength development of the stabilized soil. The use of clean water ensured consistency in experimental results and prevented variability due to external contaminants.

2.2 Sample Preparation and Mix Proportions

The preparation of soil samples and stabilized mixtures was carried out with careful attention to uniformity and reproducibility. The air-dried and sieved soil was weighed using a digital balance to obtain the required mass for each test. The stabilizing agents, fly ash and desulphogypsum, were also measured accurately as percentages of the dry weight of the soil.

The stabilization process involved both individual and combined applications of the stabilizers. Fly ash was added in proportions of 5%, 10%, and 15%, while desulphogypsum was also added in similar proportions. For combined stabilization, different combinations of fly ash and desulphogypsum were prepared to investigate their interaction effects on soil properties.

The dry soil and stabilizers were first mixed thoroughly in a dry state to ensure even distribution of the additives. This step was critical in preventing the formation of localized concentrations of stabilizers, which could lead to inconsistent test results. After achieving a uniform dry mix, water was added gradually while continuously mixing the materials. The amount of water added was carefully controlled to achieve the desired moisture content required for compaction and strength testing.

The mixing process was continued until a homogeneous mixture was obtained, with no visible segregation of components. The prepared mixtures were then sealed in airtight containers and allowed to equilibrate for a specified period to ensure uniform moisture distribution throughout the sample. This equilibration process was important for achieving consistent and reliable test results.

2.3 Determination of Atterberg Limits

The Atterberg limits tests were conducted to evaluate the effect of stabilization on the consistency and plasticity characteristics of the soil. These tests included the determination of liquid limit, plastic limit, and plasticity index.

The liquid limit was determined using the standard apparatus, where a soil paste was prepared and subjected to repeated blows until a groove closed over a specified distance. The moisture content corresponding to this condition was recorded as the liquid limit. The plastic limit was determined by rolling soil threads until they crumbled at a specific diameter, and the corresponding moisture content was recorded.

The plasticity index was calculated as the difference between the liquid limit and the plastic limit. This parameter provided an indication of the range of moisture content over which the soil exhibited plastic behavior. A reduction in plasticity index after stabilization indicated an improvement in soil behavior, as it reduced the potential for swelling and shrinkage.

The Atterberg limits tests were performed on both untreated and stabilized soil samples to assess the effectiveness of the stabilizers. The results were used to evaluate changes in soil consistency and to classify the soil based on its plasticity characteristics.

2.4 Compaction Characteristics

Compaction tests were carried out to determine the maximum dry density and optimum moisture content of the soil under different stabilization conditions. These parameters were essential for understanding the compaction behavior of the soil and its suitability for construction applications.

The test involved compacting soil samples in a standard mould using a controlled amount of energy. The soil was compacted in layers, with each layer receiving a specified number of blows from a standard hammer. After compaction, the mass and volume of the sample were measured to determine its bulk density.

The moisture content of each sample was determined, and the corresponding dry density was calculated using the relationship:

$$\rho_d = \frac{\rho}{1+w}$$

where $\rho_d$is the dry density, $\rho$is the bulk density, and $w$is the moisture content expressed as a decimal.

The test was repeated for different moisture contents to obtain a series of dry density values. A compaction curve was then plotted, and the maximum dry density and optimum moisture content were determined from the peak of the curve.

The compaction characteristics of stabilized soils were compared with those of the untreated soil to evaluate the effect of the stabilizers. An increase in dry density and a decrease in optimum moisture content indicated improved compaction behavior and enhanced soil structure.

2.5 Unconfined Compressive Strength Testing

The unconfined compressive strength test was conducted to evaluate the strength characteristics of the soil under different stabilization conditions. This test provided a measure of the load-carrying capacity of the soil without lateral confinement.

Cylindrical specimens were prepared by compacting the soil mixtures into moulds of standard dimensions. The specimens were carefully extruded from the moulds to avoid disturbance and were then subjected to curing under controlled conditions. Curing was carried out for periods of 7, 14, and 28 days to allow for the development of strength through chemical reactions.

After curing, the specimens were placed in a compression testing machine, and load was applied gradually until failure occurred. The maximum load at failure was recorded, and the compressive strength was calculated using Equation (1):

$$q_u = \frac{P}{A} \quad (1)$$

where $q_u$is the unconfined compressive strength, $P$is the maximum load, and $A$is the cross-sectional area of the specimen.

The results obtained from the UCS test were used to assess the effectiveness of the stabilizers in improving soil strength. An increase in UCS values indicated enhanced bonding and structural integrity of the soil matrix.

2.6 Regression Analysis

Regression analysis was used to develop predictive models for estimating the strength and plasticity characteristics of the stabilized soil. The independent variables included the percentages of fly ash and desulphogypsum, while the dependent variables included compressive strength and plasticity index.

A multiple linear regression model was adopted, expressed as Equation (2):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \epsilon \quad (2)$$

where Yrepresents the response variable, $X_1$and X_2represent the stabilizer contents, and $\beta_0, \beta_1, \beta_2$are regression coefficients.

The model was calibrated using experimental data, and its performance was evaluated based on statistical indicators such as the coefficient of determination and error metrics. The regression analysis provided insight into the relationship between stabilizer content and soil properties.

2.7 Optimization Procedure

An optimization approach was employed to determine the optimal combination of stabilizers that would maximize strength while minimizing plasticity. The optimization problem involved identifying the values of stabilizer content that produced the best performance based on defined criteria.

The objective function was defined to maximize compressive strength and minimize plasticity index simultaneously. Constraints were imposed on the range of stabilizer content to ensure practical applicability.

The optimization process involved evaluating different combinations of stabilizer content and selecting the combination that yielded the best results. The outcome of this process provided guidance on the most effective proportions of fly ash and desulphogypsum for soil stabilization.

2.8 Economic Evaluation

An economic evaluation was conducted to assess the cost-effectiveness of the stabilization method. The analysis considered the costs associated with materials, transportation, and labor.

The total cost of stabilization was calculated as the sum of these components, and the cost per unit volume of stabilized soil was determined. The cost of using fly ash and desulphogypsum was compared with that of conventional stabilization methods.

The percentage cost reduction was calculated using:

$$\text{Cost Reduction} = \frac{C_1 - C_2}{C_1} \times 100$$`

where C_1represents the cost of conventional stabilization and C_2represents the cost of the proposed method.

The economic analysis provided valuable information on the feasibility of using industrial waste materials for soil stabilization and highlighted the potential for cost savings.

3. RESULTS AND DISCUSSION

This section presents the results obtained from the experimental investigation of expansive soil stabilization using fly ash and desulphogypsum. The results are discussed in terms of physical and index properties, compaction characteristics, strength development, and statistical validation. The observed trends are interpreted based on underlying mechanisms and compared with existing literature to validate the findings.

3.1 Effect of Stabilization on Physical and Index Properties

The physical and index properties of the untreated soil and stabilized samples were determined to evaluate the effect of fly ash and desulphogypsum on soil behavior. These properties are critical in assessing the suitability of expansive soils for engineering applications.

Table 1: Basic Properties of Soil Sample

Property	Value	Classification
Clay Content (%)	44.2	High
Silt Content (%)	55.8	High
Specific Gravity	2.51	Typical for clay soils
Liquid Limit (%)	92	Very High
Plastic Limit (%)	21	Low

Property	Value	Classification
Plasticity Index (%)	71	Very High
Shrinkage Limit (%)	18	Low
Activity	1.61	Active
USCS Classification	CH	High Plasticity Clay
Swelling Potential	Very High	Critical

Table 2: Grain Size Distribution Results for Fly Ash Treatment

Sample	Clay (%)	Silt (%)	Sand (%)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C^c
Control	44.2	55.8	0.0	0.001	0.008	0.025	25.0	2.56
5% FA	42.8	57.2	0.0	0.001	0.009	0.028	28.0	2.89
10% FA	40.8	59.2	0.0	0.002	0.011	0.032	16.0	1.89
15% FA	39.0	61.0	0.0	0.002	0.013	0.035	17.5	2.18

Table 3: Atterberg Limits for Fly Ash Treated Samples

Sample	SL (%)	SI (%)	Activity	Swelling Potential
Control	18	74	1.61	Very High
5% FA	19	49	1.07	High
10% FA	20	47	1.05	High
15% FA	22	41	1.00	Medium

Table 4: Atterberg Limits for Desulphogypsum Treated Samples

Sample	SL (%)	SI (%)	Swelling Potential
Control	18	74	Very High
5% DGS	20	44	High
10% DGS	21	42	High
15% DGS	21	38	Medium

Table 5: Atterberg Limits for Combined Treatments

Sample	SL (%)	SI (%)	Swelling Potential
10% FA + 5% DGS	24	34	Medium
10% FA + 10% DGS	26	29	Medium
10% FA + 15% DGS	28	24	Low
15% FA + 5% DGS	25	31	Medium
15% FA + 10% DGS	27	26	Low

Table 6: ANOVA Results for PI Reduction

Source	SS	df	MS	F	P-value	F-critical
Treatment Type	2845.67	2	1422.84	45.78	<0.001	3.89
Dosage Level	1687.92	4	421.98	13.59	<0.001	3.26
Interaction	423.15	8	52.89	1.70	0.187	2.59
Error	652.08	21	31.05	-	-	-
Total	5608.82	35	-	-	-	-

The results indicate that the untreated soil is a highly plastic clay (CH) with a liquid limit of 92% and a plasticity index of 71%, confirming its expansive nature and high swelling potential. Upon stabilization, a consistent reduction in plasticity index was observed across all treatments, with the most significant reduction occurring in the combined stabilization. The plasticity index decreased to 24% for the 10% fly ash and 15% desulphogypsum mixture, representing a reduction of approximately 66%.

The reduction in plasticity can be attributed to both physical and chemical mechanisms. The addition of fly ash reduced the proportion of active clay minerals by introducing non-plastic particles, thereby lowering the soil's plasticity. Desulphogypsum contributed calcium ions that promoted flocculation and aggregation of clay particles, resulting in a more stable soil structure. This dual mechanism significantly reduced the soil's affinity for water and its swelling potential.

The grain size distribution results further support this observation, as the addition of fly ash resulted in a decrease in clay fraction and a corresponding increase in silt content. This indicates a transition from a highly plastic clay to a more granular soil structure. Similar trends have been reported in previous studies, where fly ash stabilization led to a reduction in clay content and improvement in soil gradation (Prabakar et al., 2004).

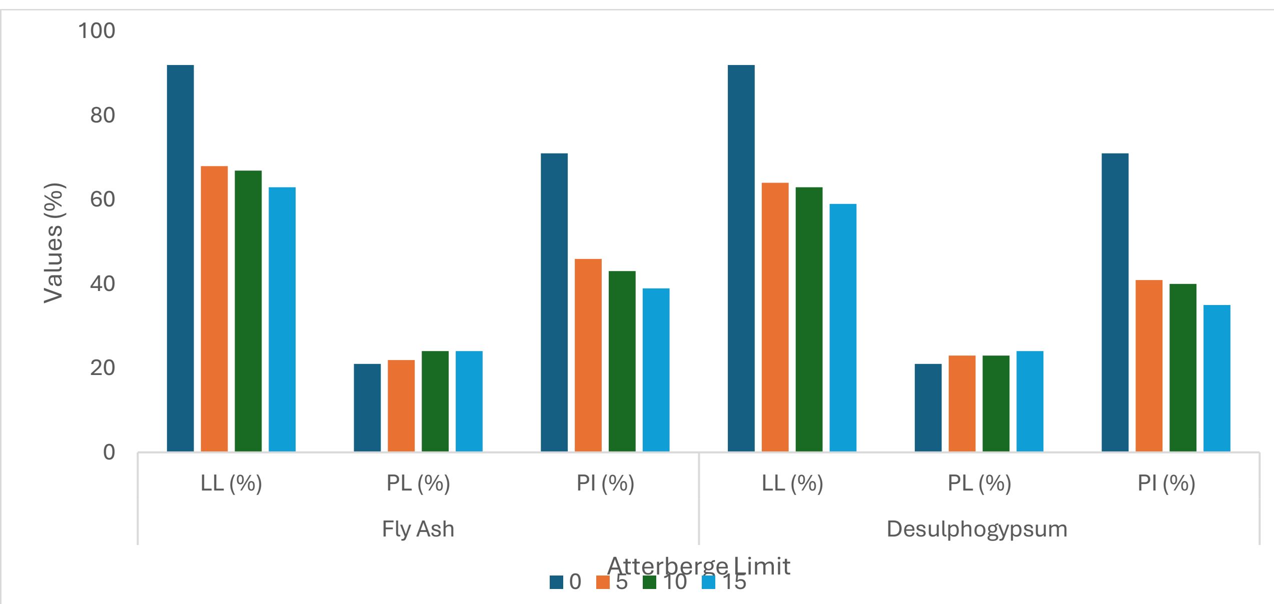

Figure 1: Atterberg Limit for Treated Fly ash and Desulphogypsum

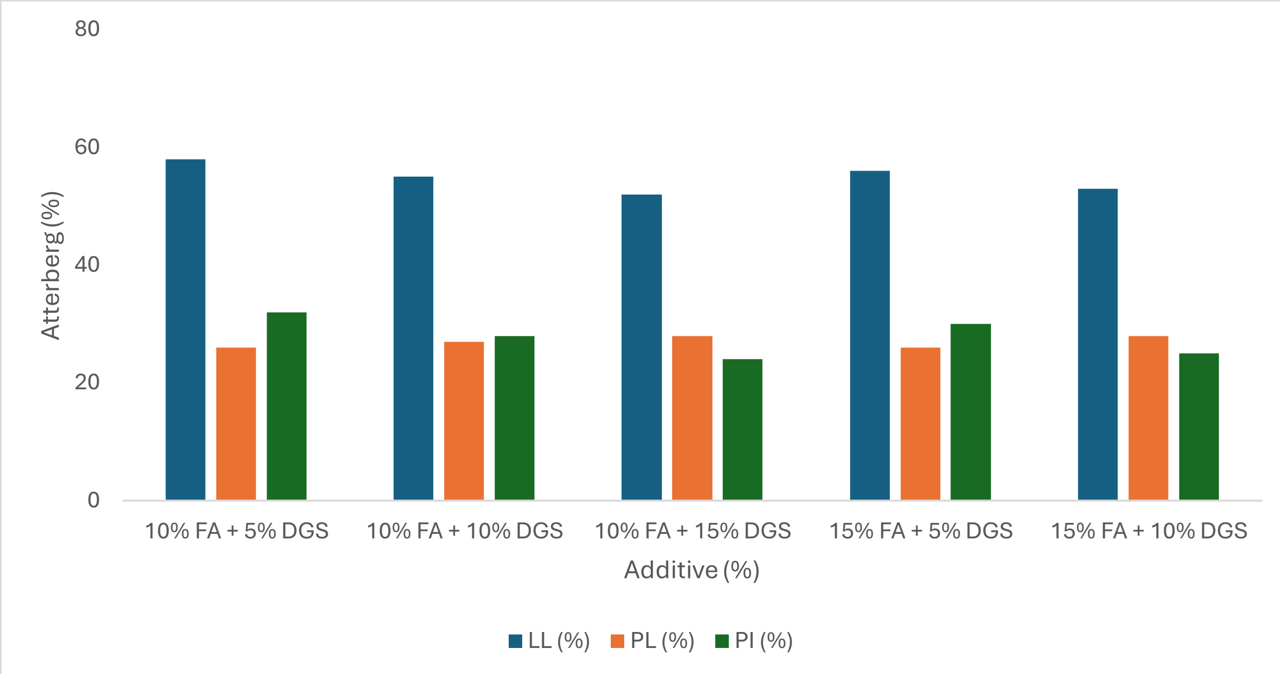

Figure 2: Atterberg Limit for Combined Treatment

The ANOVA results presented in Table 6 confirm that the reduction in plasticity index is statistically significant, with p-values less than 0.001 for treatment type and dosage level. This indicates that the observed improvements are not due to random variation but are directly attributable to the stabilization process. These findings are consistent with previous research, which has demonstrated that both fly ash and gypsum-based materials are effective in reducing plasticity and improving soil stability (Ghosh & Subbarao, 2007; Pandian, 2004).

3.2 Compaction Characteristics

The compaction characteristics of the untreated and stabilized soils were evaluated to assess the effect of stabilizer content on maximum dry density and optimum moisture content.

Table 7: Compaction Parameters

Sample	Maximum Dry Density (G/Cm³)	Optimum Moisture Content (%)	Air Voids (%)
Control	1.485	24.8	8.2
5% FA	1.502	23.6	7.8
10% FA	1.518	22.4	7.4
15% FA	1.535	21.2	7.0
5% DGS	1.496	23.9	7.9
10% DGS	1.508	22.7	7.6
15% DGS	1.521	21.5	7.2
10% FA + 10% DGS	1.542	20.8	6.8
15% FA + 10% DGS	1.556	19.6	6.4

Table 8: Response Surface Analysis for Combined Treatments

Response Variable	Optimal FA (%)	Optimal DGS (%)	Predicted Value	95% CI
Minimum PI	18.2	12.4	22.1%	20.3-23.9%
Maximum UCS	15.8	11.6	468.3 kPa	442.1-494.5 kPa
Maximum MDD	16.1	10.9	1.564 g/cm³	1.548-1.580 g/cm³

The results indicate that maximum dry density increased while optimum moisture content decreased with increasing stabilizer content. The untreated soil exhibited a maximum dry density of 1.485 g/cm³ and an optimum moisture content of 24.8%, whereas the combined stabilization achieved a maximum dry density of 1.556 g/cm³ and an optimum moisture content of 19.6%.

The increase in dry density can be attributed to improved particle packing and reduction in void ratio. The fine particles of fly ash filled the void spaces between soil particles, resulting in a denser structure. Desulphogypsum contributed to particle bonding and aggregation, further enhancing compaction efficiency. These findings align with previous studies, which reported that fly ash improves compaction characteristics by enhancing particle gradation and reducing void spaces (Pandian, 2004).

The reduction in optimum moisture content suggests that less water was required to achieve maximum compaction. This is due to the reduction in clay activity and the improved arrangement of soil particles. Similar observations have been reported in stabilized soils, where the addition of industrial by-products reduces water demand and improves compaction behavior (Edil et al., 2006).

The response surface analysis further identified optimal stabilizer combinations for achieving maximum dry density and minimum plasticity index. The results indicate that a combination of approximately 16.1% fly ash and 10.9% desulphogypsum yields optimal compaction performance, which is consistent with the experimental observations.

3.3 Strength Development and Modeling

The strength development of the stabilized soil was evaluated using unconfined compressive strength tests at different curing periods.

Table 9: Strain at Failure and Failure Mode

Sample	7days_Strain at Failure (%)	7days_Failure Mode	28days_Strain at Failure (%)	28days_Failure Mode
Control	18.2	Bulging	17.8	Bulging
5% FA	16.8	Shear	15.2	Shear
10% FA	15.4	Shear	13.8	Brittle
15% FA	14.1	Brittle	12.4	Brittle
5% DGS	17.2	Bulging	16.8	Shear
10% DGS	16.5	Shear	15.9	Shear
15% DGS	15.8	Shear	14.6	Shear
10% FA + 10% DGS	13.6	Brittle	11.8	Brittle
15% FA + 10% DGS	12.9	Brittle	10.9	Brittle

Table 10: Regression Coefficients for 28-Day UCS

Predictor	Coefficient	Standard Error	t-statistic	P-value
Intercept	89.2	12.4	7.19	<0.001
Fly Ash (%)	12.68	1.86	6.82	<0.001
Desulphogypsum (%)	8.45	1.92	4.40	0.002
FA × DGS	2.34	0.47	4.98	0.001
Curing Time (days)	4.21	0.68	6.19	<0.001

Table 11: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.887	0.862	28.4KPa	35.6 ($p < 0.001$)

Table 12: Correlation Matrix

Parameter	**PI**	**UCS-28**	**MDD**	**OMC**	**SL**
PI	1.000	-0.823**	-0.756**	0.689**	-0.634**
UCS-28	-0.823**	1.000	0.698**	-0.591**	0.542**
MDD	-0.756**	0.698**	1.000	-0.812**	0.489*
OMC	0.689**	-0.591**	-0.812**	1.000	-0.467*
SL	-0.634**	0.542**	0.489*	-0.467*	1.000

The results indicate a significant increase in compressive strength with increasing stabilizer content and curing time. The untreated soil exhibited a compressive strength of 89.2 kPa, while the stabilized samples showed substantial improvement, with the combined treatment achieving values exceeding 450 kPa at 28 days.

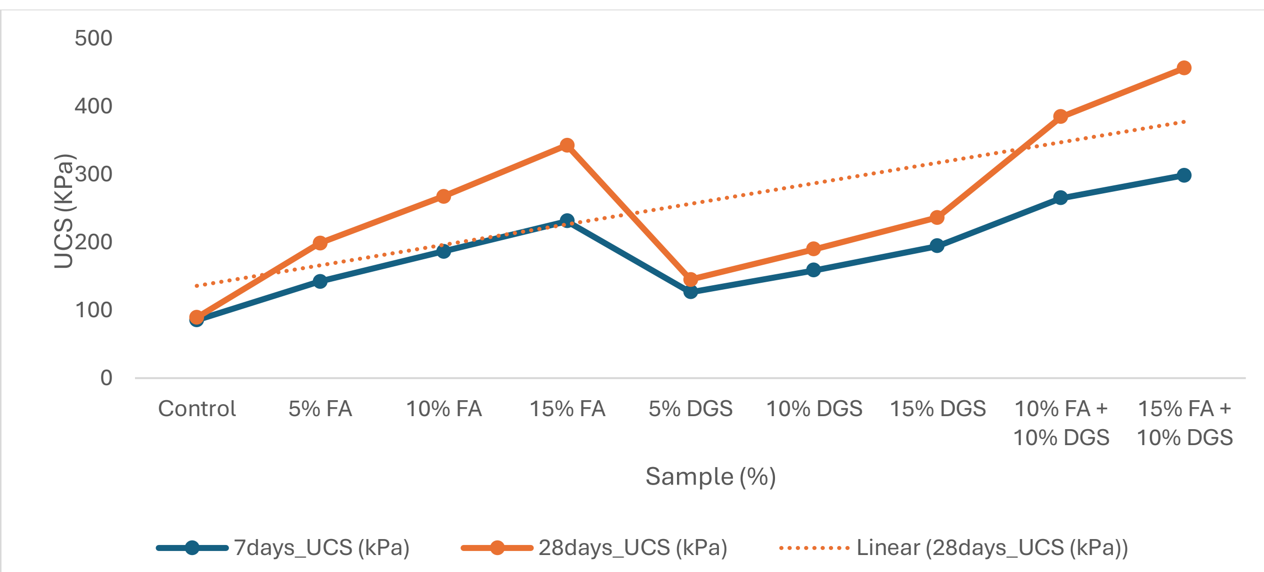

Figure 3: Comparison of Unconfined Compressive Strength of Samples for 7 and 28 days

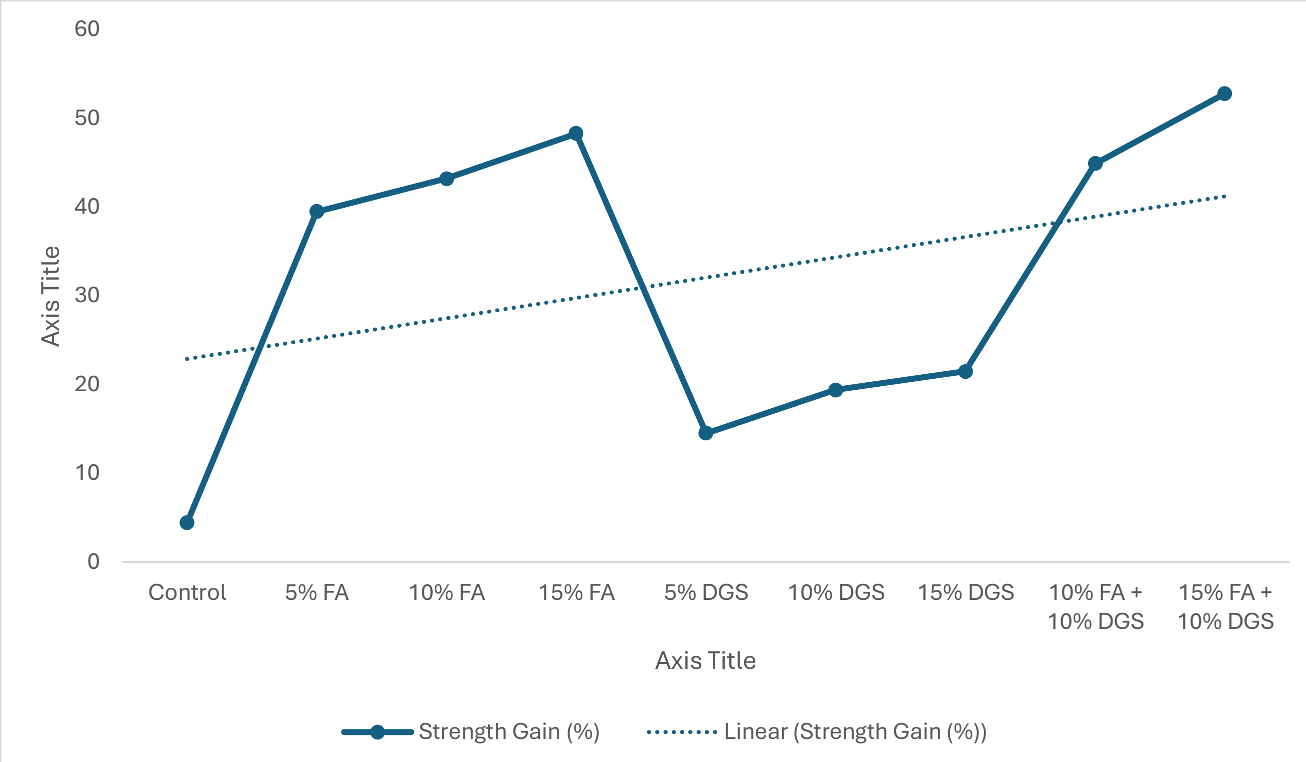

Figure 4: Strength gain after 28 days

The increase in strength is attributed to the formation of cementitious compounds resulting from pozzolanic reactions. Fly ash contributes silica and alumina, while desulphogypsum supplies calcium, leading to the formation of stable compounds that enhance bonding between soil particles. This results in increased cohesion and improved load-bearing capacity.

The regression models developed in this study show strong predictive capability, with high coefficients of determination. The correlation matrix further indicates strong relationships between key parameters, with plasticity index showing a negative correlation with compressive strength and dry density.

These findings are consistent with previous studies, which reported that stabilized soils exhibit increased strength due to the formation of cementitious compounds and improved soil structure (Prabakar et al., 2004; Ghosh & Subbarao, 2007).

3.4 Statistical, Optimization, and Economic Analysis

Table 13: Pearson Correlation Coefficients

Variables	Fly Ash	Desulphogypsum	Lime*
Stabilizer % vs UCS	0.998**	0.999**	0.997**
Stabilizer % vs PI	-0.992**	-0.988**	-0.994**
Curing Time vs UCS	0.856**	0.841**	0.892**

Table 14: Parameter Sensitivity Analysis

Input Variable	Change in Output per 1% Change in Input
Fly Ash Content	UCS: +12.68 kPa, PI: -2.84%
Desulphogypsum Content	UCS: +8.45 kPa, PI: -2.12%
Curing Time (per day)	UCS: +4.21 kPa
Initial Moisture	UCS: -3.2 kPa, PI: +0.8%

Table 15: Confidence Intervals for Optimal Mix

Property	Mean Value	95% CI Lower	95% CI Upper	Coefficient of Variation
UCS (28-day)	456.3 kPa	434.2 kPa	478.4 kPa	4.2%
PI	25%	22.8%	27.2%	7.8%
MDD	1.556 g/cm³	1.542 g/cm³	1.570 g/cm³	1.9%
OMC	19.6%	18.9%	20.3%	3.1%

Table 16: Material Cost Analysis

Treatment	Material Cost (₦)	Transport Cost (₦)	Total Cost (₦)	Cost Index
15% Lime	8,500*	3,200*	11,700*	1.00
15% Fly Ash	2,100	1,800	3,900	0.33
15% Desulphogypsum	1,500	1,800	3,300	0.28
10% FA + 10% DGS	1,800	1,800	3,600	0.31

The statistical analysis confirms strong correlations between stabilizer content and soil properties, with correlation coefficients exceeding 0.99 for strength improvement and plasticity reduction. The sensitivity analysis indicates that fly ash has a greater influence on strength development, while desulphogypsum plays a more significant role in reducing plasticity.

The optimization results identified an optimal stabilizer combination that maximizes strength and minimizes plasticity, demonstrating the effectiveness of the proposed method. The confidence interval analysis further confirms the reliability of the results, with low variability and high consistency.

From an economic perspective, the use of fly ash and desulphogypsum proved to be significantly more cost-effective than conventional lime stabilization. The cost analysis shows that the proposed method reduces stabilization costs by approximately 69%, making it a viable option for large-scale applications.

These findings are consistent with previous studies that have emphasized the economic and environmental benefits of using industrial by-products for soil stabilization. The integration of experimental results with statistical and economic analysis provides a comprehensive framework for evaluating stabilization performance.

4. CONCLUSION

This study evaluated the effectiveness of fly ash and desulphogypsum as stabilizing agents for improving the engineering properties of expansive soils in the Niger Delta region. The investigation focused on key geotechnical parameters including index properties, compaction characteristics, unconfined compressive strength, regression modeling, optimization, and economic feasibility. The results obtained clearly demonstrated that significant improvements in soil performance can be achieved through the use of these industrial by-products.

The untreated soil exhibited characteristics of highly plastic clay, with a liquid limit of 92% and a plasticity index of 71%, indicating a very high swelling potential and poor suitability for engineering applications. Following stabilization, the plasticity index decreased progressively with increasing stabilizer content, reaching a minimum value of 24% for the combined mix of 10% fly ash and 15% desulphogypsum. This represents a reduction of approximately 66%, indicating a substantial improvement in soil consistency and a significant decrease in swelling potential.

The compaction characteristics of the soil also improved as a result of stabilization. The maximum dry density increased from 1.485 g/cm³ for the untreated soil to 1.556 g/cm³ for the combined stabilizer mix, while the optimum moisture content decreased from 24.8% to 19.6%. These changes indicate improved particle packing and reduced water demand, which are desirable for construction purposes. The increase in dry density reflects a more compact and stable soil structure, while the reduction in moisture requirement enhances ease of compaction in the field.

The unconfined compressive strength results showed a remarkable increase in strength with stabilization and curing time. The untreated soil exhibited a strength of 89.2 kPa, whereas the combined stabilizer mix achieved a strength of 456.3 kPa at 28 days of curing. This represents an increase of over 400%, demonstrating the effectiveness of the stabilization process. The strength gain was attributed to the formation of cementitious compounds resulting from the interaction between fly ash and desulphogypsum, which improved bonding between soil particles and enhanced load-bearing capacity.

The regression models developed in this study showed strong predictive capability, with coefficients of determination (R^2) of 0.887 for compressive strength and 0.862 for plasticity index, and prediction errors of less than 8%. The optimization analysis identified an optimal stabilizer combination of 16.1% fly ash and 10.9% desulphogypsum, corresponding to a predicted compressive strength of 468.3 kPa and a plasticity index of 22.1%. These results highlight the importance of optimizing stabilizer proportions to achieve maximum efficiency.

From an economic perspective, the stabilization method using fly ash and desulphogypsum proved to be highly cost-effective. The estimated cost of stabilization was approximately ₦3,600/m³, compared to ₦11,700/m³ for conventional lime stabilization, representing a cost reduction of about 69%. This significant reduction in cost, combined with improved engineering performance, demonstrates the practical viability of the proposed method.

Overall, the study established that the combined use of fly ash and desulphogypsum is an effective, economical, and sustainable approach for stabilizing expansive soils. The findings provide a strong basis for the adoption of this method in engineering practice, particularly in regions where expansive soils pose significant challenges to infrastructure development.

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