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Expansive Clay Soil Stabilization Using Areca Nut Fiber Ash and Cement

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Abstract – Expansive clay soils, prevalent across several regions of India, exhibit pronounced volumetric instability upon moisture fluctuation, posing significant threats to the integrity of foundations, pavements, and other civil infrastructure. This study investigates the stabilization of expansive clay collected from Allavaram, Andhra Pradesh, India, using Areca Nut Fiber Ash (ANFA) – an agricultural by-product with inherent pozzolanic properties – combined with Ordinary Portland Cement (OPC) as a composite stabilizer. Four mix proportions were investigated: an untreated control (0% ANFA, no cement added) and three treated mixes in which OPC was held constant at 2% by dry weight of soil while ANFA content was varied at 5%, 7.5%, and 10%; all stabilizer percentages are expressed by dry weight of soil. Tests covering Specific Gravity, Differential Free Swell, Atterberg Limits, Standard Proctor Compaction, and California Bearing Ratio were conducted as per IS standards. The Differential Free Swell decreased substantially from 80% for untreated soil to 21% at 10% ANFA, confirming effective suppression of expansive behavior. The Liquid Limit decreased from 70% to 57% while the Plastic Limit increased from 30.25% to 45.8%, resulting in a dramatic reduction in Plasticity Index from 39.75% to 11.2% at 10% ANFA, indicating greatly reduced shrink-swell susceptibility. The Optimum Moisture Content reached a minimum of 12.24% at 5% ANFA and the Maximum Dry Density peaked at 1.74 g/cc at the same dosage, identifying 5% ANFA as the optimum proportion for field compaction. The unsoaked CBR increased from 3.8% for untreated soil to a peak of 7.9% at 7.5% ANFA content, with soaked CBR improving from 2.1% to 5.2% at the same dosage, confirming significant improvement in subgrade load-bearing capacity under both field and adverse moisture conditions. The results establish ANFA combined with a fixed 2% OPC dosage as an effective, economical, and eco-friendly stabilization system for expansive clay soils.

Keywords**:** Expansive Clay Soil, Soil Stabilization, Areca Nut Fiber Ash, Pozzolanic Reaction, Differential Free Swell, Atterberg Limits, Plasticity Index, Maximum Dry Density, Optimum Moisture Content, California Bearing Ratio, Black Cotton Soil, Sustainable Geotechnics.

I. INTRODUCTION

Expansive clay soils present one of the most demanding conditions in geotechnical engineering, owing to the presence of montmorillonite clay minerals that absorb water and swell upon wetting, then shrink and crack upon drying (Chakraborty, 2016). This cyclic volumetric behavior generates differential settlement, uplift pressures, and progressive structural damage to foundations, road pavements, and embankments (Chakraborty, 2016; Yusuf & Zava, 2019). Globally, expansive soils are estimated to affect infrastructure across more than 40 countries, causing annual repair and maintenance expenditures that exceed those attributable to floods, earthquakes, and hurricanes combined (Gidebo, Yasuhara, & Kinoshita, 2023). Such soils are widespread across India, particularly in the coastal alluvial plains of Andhra Pradesh, where deltaic clay deposits of the Godavari River system create substantial challenges for infrastructure development. In Konaseema district, specifically around Allavaram, saturated conditions during the monsoon cause rapid bearing capacity loss, while desiccation cracking in dry periods leads to continuous deterioration of overlying structures. The scale and recurrence of this problem underscore the need for stabilization solutions that are not only technically effective but also economically and environmentally sustainable, particularly in regions where construction budgets and material availability are constrained.

Conventional stabilization using lime or cement remains the most established practice. Both materials function through cation exchange, flocculation, and pozzolanic reactions that produce calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) compounds, binding soil particles and reducing plasticity (Chakraborty, 2016; Yusuf & Zava, 2019). The stabilization process involves two distinct stages: immediate cation exchange and flocculation that reduce plasticity, followed by time-dependent pozzolanic bonding that progressively increases strength (Chakraborty, 2016; Yusuf & Zava, 2019). However, cement manufacturing contributes approximately 8% of global CO_2 emissions (Shyam et al., 2024), and the associated material costs constrain rural infrastructure budgets, motivating the search for greener alternatives. In this context, industrial waste by-products have also attracted research attention: alum sludge, generated in bulk by water treatment plants, has been demonstrated as a low-cost soil stabilizer capable of improving bearing capacity and plasticity of expansive clays while simultaneously addressing waste disposal challenges within a circular economy framework (Aamir et al., 2019). Findings such as these reinforce the broader argument that the geotechnical reuse of industrial and agricultural waste streams can simultaneously serve engineering, environmental, and economic goals.

Agricultural waste ashes rich in amorphous silica have received considerable research attention as eco-friendly pozzolanic stabilizers (Dauda & Dominic, 2022; Gidebo et al., 2023; Yusuf & Zava, 2019). Their high silica content enables pozzolanic reactions with the calcium hydroxide present in soil or released by supplementary cement, generating C-S-H gel that densifies the soil matrix and reduces its sensitivity to moisture (Dauda & Dominic, 2022). Rice husk ash (RHA), containing 85–90% SiO_2, has been shown to achieve substantial strength improvement at dosages competitive with cement (Jiang, Huang, Ma, & Luo, 2019; Abdulrahman, Al-Kaream, & Ihsan, 2024). Coconut husk ash (CHA) at 8% dosage delivered a 50% reduction in differential free swell and a near doubling of unconfined compressive strength relative to untreated soil (Chakraborty, 2016; Yusuf & Zava, 2019). Bagasse ash, the incineration residue of sugarcane processing waste, is another well-studied agricultural stabilizer: research on black cotton soils has confirmed consistent improvements in California Bearing Ratio and compressive strength when bagasse ash is used either as a standalone additive or in combination with cement, with optimal dosages typically falling between 4% and 12% by dry weight of soil (Kharade, Suryavanshi, Gujar, & Deshmukh, 2014; Kiran & Kiran, 2013). Areca nut-derived additives have also demonstrated consistent efficacy: fiber inclusion improved unconfined compressive strength, CBR, and tensile strength through enhanced particle interlocking (Sudhakaran, Sharma, & Kolathayar, 2018; Balreddy, Sajjan, Pruthviraja, & Naganna, 2024; Narayan et al., 2024), while areca nut husk ash (ANFA), containing 60–75% silica depending on combustion conditions (Shyam et al., 2024), confirmed effective soil property improvement when combined with cement (Ranjith & Harish, n.d.). India accounts for approximately 54% of global areca nut production (Shyam et al., 2024), generating large volumes of husk waste that currently pose serious environmental disposal challenges. The convergence of pozzolanic reactivity, local availability, and waste diversion potential makes ANFA a particularly compelling candidate for infrastructure applications in areca-nut-producing regions such as coastal Andhra Pradesh.

Combined stabilization systems incorporating both an agricultural pozzolan and cement consistently outperform single-additive treatments. Cement ensures rapid early-strength gain through hydration, while the pozzolanic material sustains long-term microstructural densification (Islam, Hoque, Uddin, & Chowdhury, 2018). This synergistic behavior ensures early load-bearing capacity along- side continued durability development, making combined systems particularly suitable for high-plasticity expansive clays (Islam et al., 2018; Chakraborty, 2016). The dual-component approach also allows the cement fraction to be minimized, reducing both cost and carbon footprint, while the agricultural ash fraction simultaneously addresses a waste management challenge, aligning the stabilization strategy with sustainable construction principles (Dauda & Dominic, 2022; Gidebo et al., 2023). Despite the body of existing research, systematic investigation of ANFA–OPC combinations applied to expansive clay soils of the Konaseema coastal region remains limited (Ranjith & Harish, n.d.; Shyam et al., 2024).

The present study addresses this gap by evaluating the combined stabilizing effect of ANFA and OPC on expansive clay from Allavaram, Andhra Pradesh. Four mix proportions were tested: an untreated control (0% ANFA, no cement) and three treated mixes with OPC fixed at 2% while ANFA was varied at 5%, 7.5%, and 10% by dry weight of soil. Specific Gravity, Differential Free Swell, Atterberg Limits, Standard Proctor Compaction, and California Bearing Ratio tests were conducted in accordance with IS standards to assess changes in swelling behavior, plasticity, compaction, and subgrade load-bearing characteristics.

II. MATERIALS AND METHODOLOGY

2.1 Materials

2.1.1 Expansive Clay Soil

Expansive clay is a type of soil that undergoes significant volume change—swelling when wet and shrinking when dry—due to the presence of water-absorbent clay minerals like montmorillonite. This cyclic behavior can cause severe damage to lightweight structures, pavements, and foundations by exerting high swelling pressure.

Table 1 Index properties of untreated expansive clay soil

Property (1)	Value (2)
Color	Dark greyish black
Specific Gravity (G_s)	2.67
Natural Moisture Content (%)	27.4
Liquid Limit (%)	70
Plastic Limit (%)	30.25
Plasticity Index (%)	39.75
Differential Free Swell (%)	80
IS Classification (IS 1498)	CH

2.1.2 Areca Nut Fiber Ash (ANFA)

Areca nut ash is a pozzolanic material derived from the controlled combustion of areca nut husks, a widely available agricultural waste in tropical regions. Rich in silica and other reactive oxides, it possesses the ability to chemically modify soil properties when used as an additive. This makes it a promising, eco-friendly stabilizer for improving the engineering behavior of problematic soils like expansive clay.

Table 2 Properties of Areca Nut Fiber Ash (ANFA)

Property (1)	Value (2)
Color	Light grey
Specific Gravity	2.18
SiO_2 Content (%)	68.4
Fineness (passing 75 μm sieve, %)	96
Loss on Ignition, LOI (%)	5.2
pH	10.8

2.1.3 Ordinary Portland Cement (OPC)

53-grade Ordinary Portland Cement conforming to IS 12269:2013 was employed as a supplementary binding agent to activate the pozzolanic potential of ANFA, provide early-strength calcium hydroxide, and accelerate cementitious bond formation within the stabilized soil matrix. Properties of the OPC as determined in the laboratory are presented in Table 3.

Table 3 Properties of OPC 53 Grade (IS 12269:2013)

Property (1)	Value (2)
Specific Gravity	3.15
Normal Consistency (%)	30
Initial Setting Time (min)	48
Final Setting Time (min)	280
Fineness, residue on 90 μm sieve (%)	2.8
28-day Compressive Strength (MPa)	53.4

2.1.4 Water

Potable water was used for mixing across all specimen preparation and laboratory testing procedures.

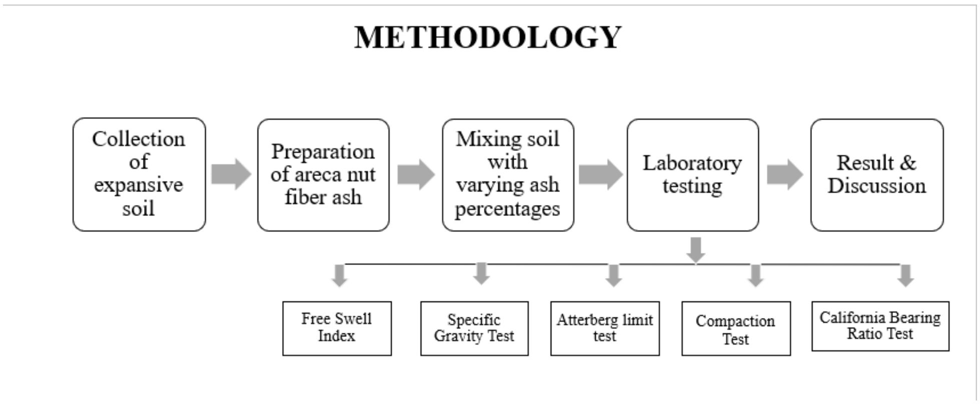

Figure 1 Flowchart representation of expansive clay soil stabilization.

2.2 Methodology

2.2.1 Collection of Expansive Soil

Expansive clay soil was collected from Allavaram, Konaseema district, Andhra Pradesh, India, a region characterized by deltaic clay deposits of the Godavari River system that exhibit pronounced volumetric instability under seasonal moisture fluctuations. Bulk samples were collected from a depth of 0.5–1.0 m below the natural ground surface using hand excavation to avoid disturbance of the natural fabric. Prior to collection, the top layer of vegetation and organic matter was removed to ensure representative sampling of the native subgrade clay. The collected soil was air-dried, pulverized, and passed through a 4.75 mm IS sieve to remove coarse fragments and organic debris. Representative sub-samples were retained for index property characterization, and the remainder was stored in airtight containers to preserve its natural moisture condition for subsequent testing.

2.2.2 Preparation of Areca Nut Fiber Ash (ANFA)

Areca nut husks were procured from local processing units in the Konaseema region, where areca nut cultivation is widespread and husk disposal constitutes a significant agricultural waste management challenge. The husks were first sun-dried for 48 hours to eliminate surface moisture, and then subjected to controlled combustion in an open kiln at temperatures in the range of 600–700°C to ensure complete burnout of organic matter while retaining an amorphous silica-rich ash structure. Combustion at temperatures below 800°C is critical to preserve the amorphous phase of silica, which governs pozzolanic reactivity; crystallization of silica at higher temperatures reduces its chemical activity significantly. The resulting ash was cooled to ambient temperature, ground using a ball mill, and sieved through a 75 μm IS sieve to achieve a fineness suitable for soil treatment. The as-prepared ANFA was characterized for specific gravity, silica content (SiO_2), loss on ignition (LOI), fineness, and pH; the results are presented in Table 2. The high silica content (68.4%) and elevated pH (10.8) confirm the pozzolanic character of the ash, consistent with values reported for similar agricultural ash materials.

2.2.3 Mixing Soil with Varying ANFA–OPC Proportions

The stabilizer system consisted of Ordinary Portland Cement (OPC) held constant at 2% by dry weight of soil in all treated mixes, combined with varying proportions of ANFA. The untreated control (0% ANFA) contained no admixtures of any kind. The three treated mix proportions investigated were: 5% ANFA + 2% OPC, 7.5% ANFA + 2% OPC, and 10% ANFA + 2% OPC, designated M5, M7.5, and M10 respectively; the untreated soil is designated M0. All stabilizer percentages are expressed by dry weight of soil. The cement content was held constant from 5% ANFA onwards to isolate the effect of increasing ANFA dosage on soil engineering properties, while ensuring a consistent supply of $Ca(OH)_2$ to activate ANFA's pozzolanic silica. For each treated mix, the required quantities of ANFA, OPC, and oven-dried soil were weighed and dry-blended thoroughly using a mechanical mixer until a visually uniform distribution of the stabilizers was achieved. Potable water was then added incrementally to bring the mixture to the target moisture content for each test, and blending was continued until a homogeneous paste was obtained. All specimens were prepared and tested within 30 minutes of water addition to minimize pre-test hydration effects. This procedure was repeated independently for each test type at each mix proportion.

2.2.4 Laboratory Testing

A comprehensive suite of laboratory tests was conducted on both the untreated soil and all three treated mixes in accordance with relevant IS standards, covering index properties, plasticity characteristics, swelling behaviour, and compaction response. The **Differential Free Swell (DFS)** test was carried out as per IS 2720 (Part 40) by placing 10 g of dry soil in each of two graduated cylinders – one filled with kerosene and one with distilled water – and recording the swollen volume after 24 hours; the DFS was computed as:

$$DFS = \frac{V_w - V_k}{V_k} \times 100 \qquad (1)$$

where V_w and V_k are the final volumes in water and kerosene respectively. The **Specific Gravity (G_s)** of soil solids was determined using the pycnometer (density bottle) method as per IS 2720 (Part 3), in triplicate, using the relation:

$$G_s = \frac{W_2 - W_1}{(W_2 - W_1) - (W_3 - W_4)} \qquad (2)$$

where W_1 is the mass of the empty pycnometer, W_2 the mass with soil, W_3 the mass with soil and distilled water, and W_4 the mass with distilled water only. The **Atterberg Limits** – Liquid Limit (LL) and Plastic Limit (PL) – were determined as per IS 2720 (Part 5) using the Casagrande percussion cup method at 25 blows and the thread-rolling method at 3 mm thread diameter respectively, with the Plasticity Index computed as:

$$PI = LL - PL \qquad (3)$$

All samples for Atterberg limit testing were prepared from soil passing a 425 μm IS sieve. The **Standard Proctor Compaction Test** was performed as per IS 2720 (Part 7) using a 1000 cm^3 cylindrical mould, a 2.6 kg rammer with a drop height of 310 mm, and three compaction layers each receiving 25 blows, to establish the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for each mix.

The **California Bearing Ratio (CBR)** test was conducted as per IS 2720 (Part 16) on specimens compacted at their respective OMC using IS light compaction (three layers, 55 blows per layer, 2.6 kg hammer). The mould with base plate was placed under the penetration plunger and a surcharge weight of 2.5 kg was applied. The load penetration machine was operated at a uniform rate of 1.25 mm/min and load readings were recorded at penetration increments of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 7.5, 10.0, and 12.5 mm. The load–penetration curve was plotted for each specimen and unit load values at 2.5 mm and 5.0 mm penetration were read from the graph. The CBR value was calculated as the ratio of the measured test load to the standard load at the respective penetration depth, expressed as a percentage:

$$CBR = \frac{\text{Test Load}}{\text{Standard Load}} \times 100 \qquad (4)$$

The standard reference loads adopted in accordance with IS 2720 (Part 16) are presented in Table 4. The higher of the two CBR values (at 2.5 mm and 5.0 mm penetration) was adopted as the governing CBR for each mix. Both unsoaked and soaked CBR tests were conducted for all four mix proportions. For the soaked condition, compacted specimens were submerged in water for 96 hours under a 2.5 kg surcharge load prior to penetration, to evaluate subgrade load-bearing capacity under worst-case moisture conditions.

Table 4 Standard reference loads for CBR test (IS 2720 Part 16)

Penetration (mm) (1)	Standard Load (kg) (2)	Unit Standard Load (kg/cm^2) (3)
2.5	1370	70
5.0	2055	105
7.5	2630	134
10.0	3180	162
12.5	3600	183

III. RESULTS AND DISCUSSION

3.1 Specific Gravity

Table 5 Variation of specific gravity with ANFA–OPC dosage

Mix (1)	Specific Gravity (G_s) (2)
M0 (0% ANFA)	2.67
M5 (5% ANFA)	2.62
M7.5 (7.5% ANFA)	2.58
M10 (10% ANFA)	2.54

Note: OPC content fixed at 2% in all treated mixes (M5, M7.5, M10); M0 is untreated soil with no admixtures. Gs of ANFA = 2.18; Gs of native soil = 2.67.

The specific gravity of the soil–ANFA–OPC mixes decreased progressively from 2.67 (M0) to 2.54 (M10) with increasing ANFA dosage, as presented in Table 5. This consistent reduction is attributable to the inherently lower specific gravity of ANFA (2.18) relative to the native soil grains (2.67): as ANFA progressively displaces a greater proportion of the denser soil mineral fraction, the composite specific gravity of the mix shifts downward in proportion to the substituted volume. Notably, the marginal and uniform nature of this decline confirms that ANFA introduces no heavy mineral phases into the matrix that could distort void ratio calculations or subsequent compaction analysis. The quadratic regression fitted to the data, $y = -0.0005x^2 - 0.0077x + 2.6703$ ($R^2 = 0.9991$), confirms a highly consistent dilution effect across all tested mix proportions, with the near-zero quadratic coefficient indicating that the response remains effectively proportional over the tested dosage range.

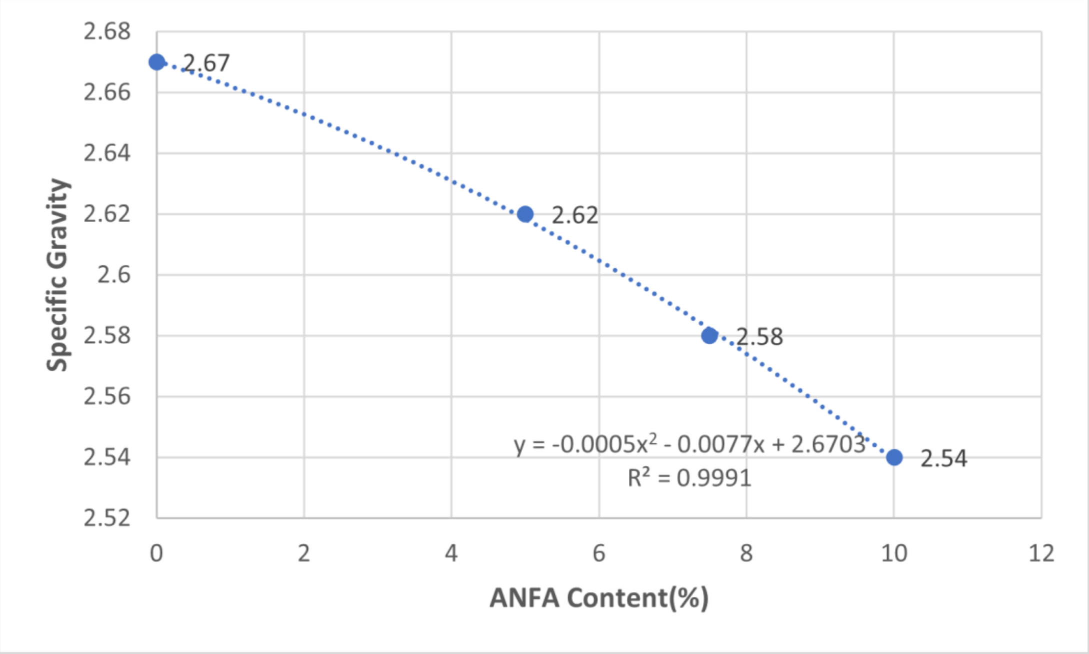

Figure 2 Variation of Specific Gravity with Areca Nut Fiber Ash Content.

3.2 Differential Free Swell

Table 6 Variation of Differential Free Swell with ANFA–OPC dosage

Mix (1)	Differential Free Swell (%) (2)
M0 (0% ANFA)	80.0
M5 (5% ANFA)	35.0
M7.5 (7.5% ANFA)	25.5
M10 (10% ANFA)	21.0

Note: OPC content fixed at 2% in all treated mixes; M0 is untreated soil with no admixtures. Overall DFS reduction from M0 to M10 = 73.75%.

The DFS of the untreated soil (M0) was 80%, confirming a highly expansive CH-class montmorillonite-bearing clay; progressive stabilization produced a steep and monotonic reduction to 21% at M10, representing an overall suppression of 73.75% relative to the untreated baseline, as presented in Table 6. The initial sharp decline at low ANFA dosages is governed by cation exchange: Ca^{2+} released during OPC hydration replaces mono- and divalent exchangeable cations on the montmorillonite surface, compressing the diffuse double layer and reducing the inter-particle repulsion that drives water absorption and swelling. At higher ANFA dosages, the pozzolanic reaction between ANFA's amorphous silica and available $Ca(OH)_2$ generates C-S-H gel that encapsulates clay aggregates and provides a physical barrier against further moisture ingress, sustaining the reduction in swell potential beyond the range where surface cation sites approach saturation. The quadratic regression $y = 0.6x^2 - 11.86x + 79.9$ ($R^2 = 0.9995$) captures this behavior precisely: the steep negative slope at low dosages reflects rapid cation-exchange-driven suppression, while the decelerating curvature at higher dosages is consistent with a transition to the slower, gel-encapsulation-dominated mechanism.

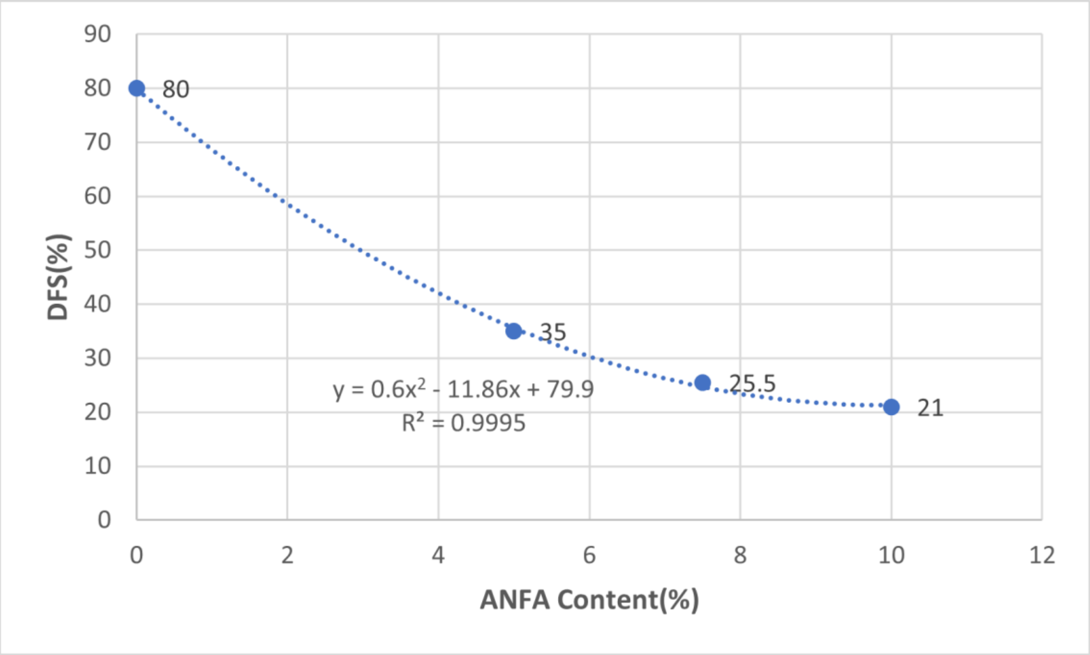

Figure 3 Variation of Differential Free Swell with Areca Nut Fiber Content.

3.3 Atterberg Limits

Table 7 Variation of Atterberg limits with ANFA–OPC dosage

Mix (1)	Liquid Limit (%) (2)	Plastic Limit (%) (3)	Plasticity Index (%) (4)
M0 (0% ANFA)	70	30.25	39.75
M5 (5% ANFA)	62	36.4	25.6
M7.5 (7.5% ANFA)	58	41.2	16.8
M10 (10% ANFA)	57	45.8	11.2

Note: OPC content fixed at 2% in all treated mixes; M0 is untreated soil with no admixtures. PI = LL − PL. PI of 11.2% at M10 is within the acceptable range for stabilized subgrade in pavement design practice.

The Atterberg limit results presented in Table 7 show opposing but complementary trends in LL and PL with increasing ANFA dosage: the LL decreased monotonically from 70% (M0) to 57% (M10), while the PL increased from 30.25% (M0) to 45.8% (M10), resulting in a dramatic compression of the PI from 39.75% (M0) to 11.2% (M10) over the same range. The decline in LL is driven by cation exchange initiated by Ca^{2+} released from OPC hydration: as monovalent surface cations on clay platelets are replaced by divalent Ca^{2+}, the thickness of the adsorbed water film surrounding each particle is reduced, directly lowering the moisture content at which the soil transitions to a liquid state. Conversely, the progressive increase in PL is attributed to the formation of pozzolanic C-S-H gel products that coat and stiffen clay platelet surfaces: the stiffened inter-particle contacts require a higher moisture content to achieve the deformable-without-cracking condition that defines the plastic state, raising the PL with each increment of ANFA. The net effect on PI is therefore the result of a dual-mechanism modification operating simultaneously on both consistency boundaries

— not a single dominant reaction — and the final PI of 11.2% at M10 falls within the range generally accepted for stabilized subgrade materials in pavement design practice. The regressions $y = 0.0764x^2 - 2.0964x + 70.082$ ($R^2 = 0.993$) for LL and $y = 0.0576x^2 + 0.9934x + 30.213$ ($R^2 = 0.9989$) for PL confirm the high dose-dependence and predictability of both trends, while the PI regression $y = 0.0187x^2 - 3.0897x + 39.869$ ($R^2 = 0.9967$) quantifies the combined narrowing of the plastic range as a single index.

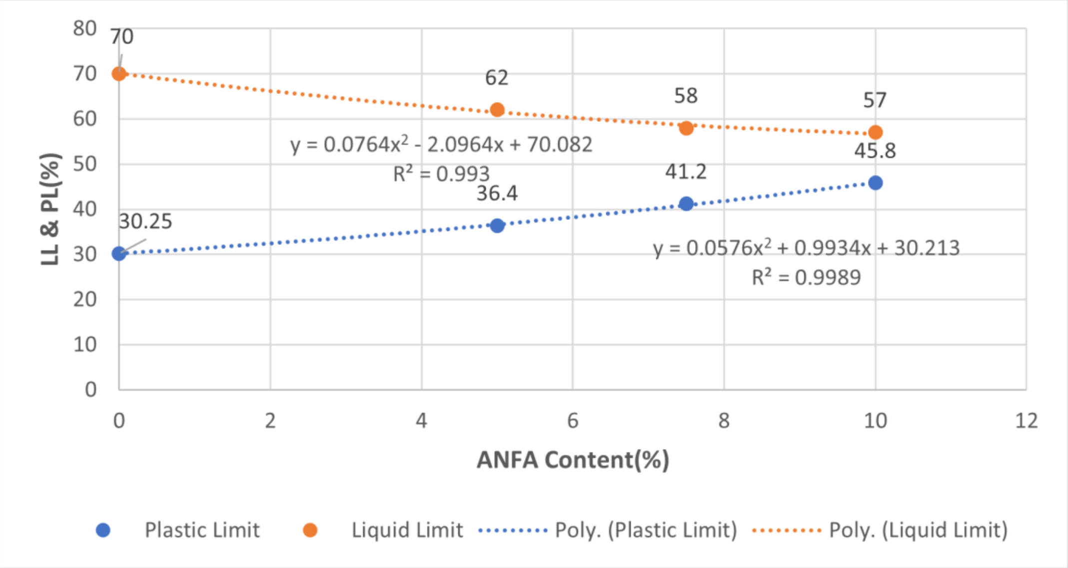

Figure 4 Variation of Liquid Limit Plastic Limit with Areca Nut Fiber Ash Content.

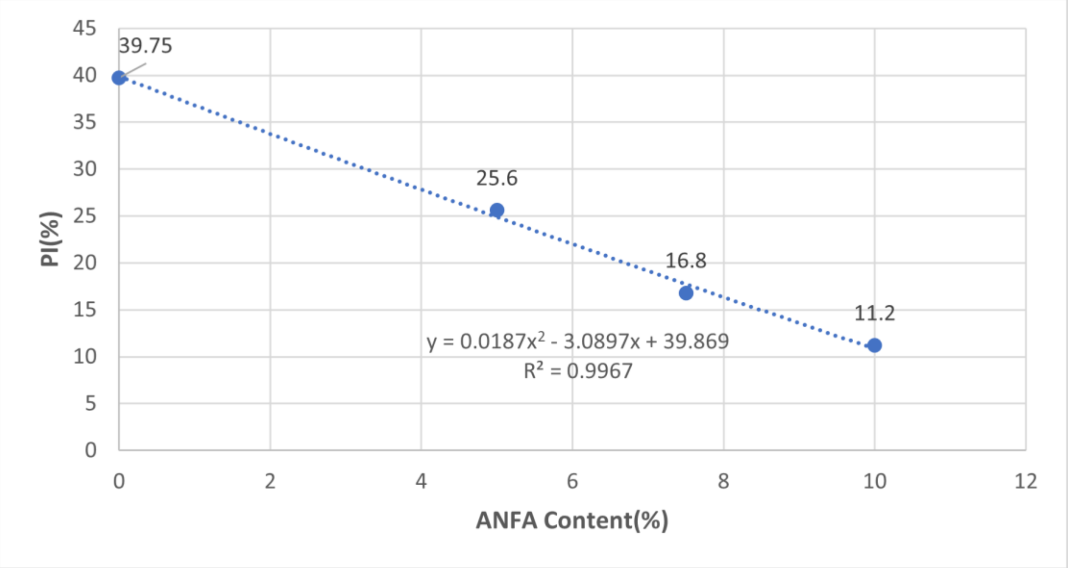

Figure 5 Variation of Plasticity Index with Areca Nut Fiber Ash Content.

3.4 Proctor Compaction

Table 8 Variation of compaction characteristics with ANFA–OPC dosage

Mix (1)	OMC (%) (2)	MDD (g/cc) (3)
M0 (0% ANFA)	18.00	1.57
M5 (5% ANFA)	12.24	1.74
M7.5 (7.5% ANFA)	14.20	1.69
M10 (10% ANFA)	16.67	1.64

Note: OPC content fixed at 2% in all treated mixes; M0 is untreated soil with no admixtures. Peak MDD (1.74 g/cc) and minimum OMC (12.24%) both occur at M5, identifying 5% ANFA as the compaction optimum.

The compaction characteristics presented in Table 8 exhibit a non-monotonic response with increasing ANFA dosage: OMC decreased from 18% (M0) to a minimum of 12.24% at M5, then rose back to 16.67% at M10, while MDD followed the inverse pattern, rising from 1.57 g/cc (M0) to a peak of 1.74 g/cc at M5 and subsequently declining to 1.64 g/cc at M10, identifying 5% ANFA as the compaction optimum. At the optimum dosage, OPC hydration rapidly generates $Ca(OH)_2$ that initiates cation exchange and flocculation of clay particles, while the early pozzolanic reaction produces C-S-H gel that infills inter-particle voids and densifies the matrix; the simultaneous chemical consumption of free water by hydration and early pozzolanic reactions reduces the total moisture demand, producing a lower OMC and higher MDD relative to the untreated soil. Beyond 5% ANFA, excess unreacted ash particles act as inert bulking agents: they interrupt the continuity of the cementitious C-S-H network, introduce finer particles that increase the water demand for adequate lubrication, and occupy pore space in a disorganized manner — collectively causing the OMC to rise and the MDD to decline with each increment of ANFA above the optimum. The cubic regressions $y = -0.0217x^3 + 0.5298x^2 - 3.2577x + 18$ ($R^2 = 1$) for OMC and $y = 0.0007x^3 - 0.0162x^2 + 0.097x + 1.57$ ($R^2 = 1$) for MDD both reproduce the non-monotonic trend with exact fidelity and mathematically locate the compaction optimum at 5% ANFA, consistent with the experimental observations.

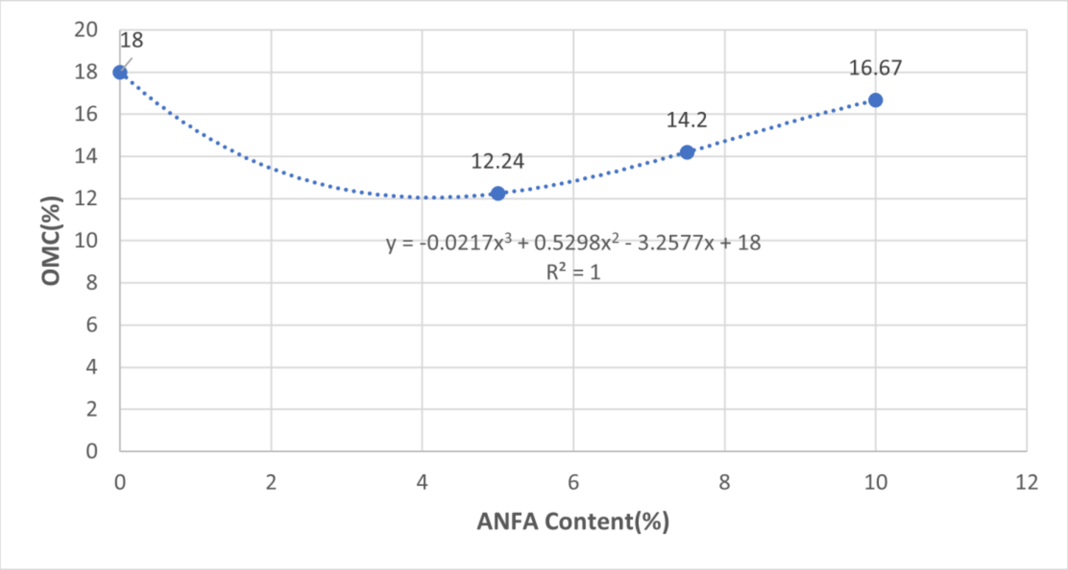

Figure 6 Variation of OMC with Areca Nut Fiber Ash Content.

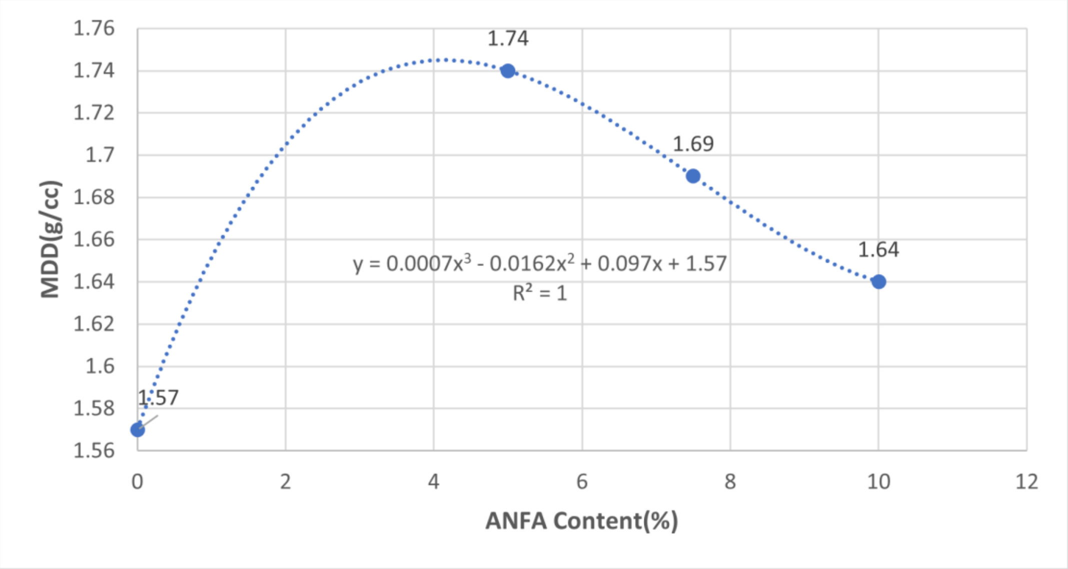

Figure 7 Variation of MDD with Areca Nut Fiber Ash Content.

3.5 California Bearing Ratio

CBR test results under both unsoaked and soaked conditions for all four mix proportions are presented in Tables 9 and 10 respectively. In every case the CBR value at 2.5 mm penetration exceeded the 5.0 mm value and was therefore adopted as the governing CBR, consistent with IS 2720 (Part 16).

3.5.1 Unsoaked CBR

Table 9 Variation of unsoaked CBR with ANFA–OPC dosage

Mix (1)	CBR at 2.5 mm (%) (2)	CBR at 5.0 mm (%) (3)	Adopted CBR (%) (4)
M0 (0% ANFA)	3.8	3.5	**3.8**
M5 (5% ANFA)	5.6	5.2	**5.6**
M7.5 (7.5% ANFA)	7.9	7.4	**7.9**
M10 (10% ANFA)	7.2	6.8	**7.2**

Note: Standard loads at 2.5 mm and 5.0 mm penetration are 1370 kg and 2055 kg respectively (IS 2720 Part 16). Adopted CBR = governing value at 2.5 mm in all cases. Peak unsoaked CBR at M7.5 represents a 108% improvement over the untreated baseline. OPC fixed at 2%; M0 is untreated soil with no admixtures.

The unsoaked CBR increased from 3.8% (M0) to a peak of 7.9% at M7.5, representing an improvement of approximately 108% over the untreated baseline, before declining marginally to 7.2% at M10, as presented in Table 9. The progressive im- provement up to M7.5 is driven by the formation of cementitious C-S-H and C-A-H compounds from the pozzolanic reaction between ANFA's amorphous silica and calcium hydroxide released during OPC hydration: these gel products coat and bond soil particles, progressively increasing inter-particle friction and overall matrix stiffness with each increment of ANFA. The marginal decline from M7.5 to M10 indicates that beyond the optimum, excess ANFA dilutes the available Ca^{2+} supply and introduces unreacted ash particles that disrupt the continuity of cementitious bonding, reducing penetration resistance. The cubic regression $y = -0.0315x^3 + 0.468x^2 - 1.1933x + 3.8$ ($R^2 = 1$) reproduces the non-monotonic trend exactly and confirms 7.5% ANFA as the optimum stabilizer proportion for unsoaked subgrade strength.

3.5.2 Soaked CBR

Table 10 Variation of soaked CBR with ANFA–OPC dosage (96-hour soak)

Mix (1)	CBR at 2.5 mm (%) (2)	CBR at 5.0 mm (%) (3)	Adopted CBR (%) (4)
M0 (0% ANFA)	2.1	1.9	**2.1**
M5 (5% ANFA)	3.4	3.1	**3.4**
M7.5 (7.5% ANFA)	5.2	4.8	**5.2**
M10 (10% ANFA)	4.7	4.3	**4.7**

Note: Specimens submerged for 96 hours under 2.5 kg surcharge prior to penetration. Standard loads as per IS 2720 Part 16. Adopted CBR = governing value at 2.5 mm in all cases. Peak soaked CBR at M7.5 represents a 148% improvement over the untreated soaked baseline. M0 is untreated soil with no admixtures.

Under 96-hour soaked conditions, the CBR increased from 2.1% (M0) to a peak of 5.2% at M7.5 — a 148% improvement over the soaked untreated baseline — before declining marginally to 4.7% at M10, as presented in Table 10. The reduction in absolute CBR values relative to the unsoaked condition at each dosage level is consistent with partial disruption of cementitious gel bonding under saturation, as adsorbed water weakens effective inter-particle stress. Critically, however, the stabilized mixes retain substantial strength even under full saturation — a direct consequence of the pozzolanic C-S-H gel framework being sufficiently mature and continuous to resist dissolution under prolonged submersion — confirming the durability of the ANFA–OPC stabilized matrix under the most adverse moisture conditions expected in the field. The cubic regression $y = -0.0245x^3 + 0.368x^2 - 0.9667x + 2.1$ ($R^2 = 1$) mirrors the unsoaked trend in form, with the consistent vertical offset between the two curves quantifying the strength penalty imposed by saturation at each dosage level.

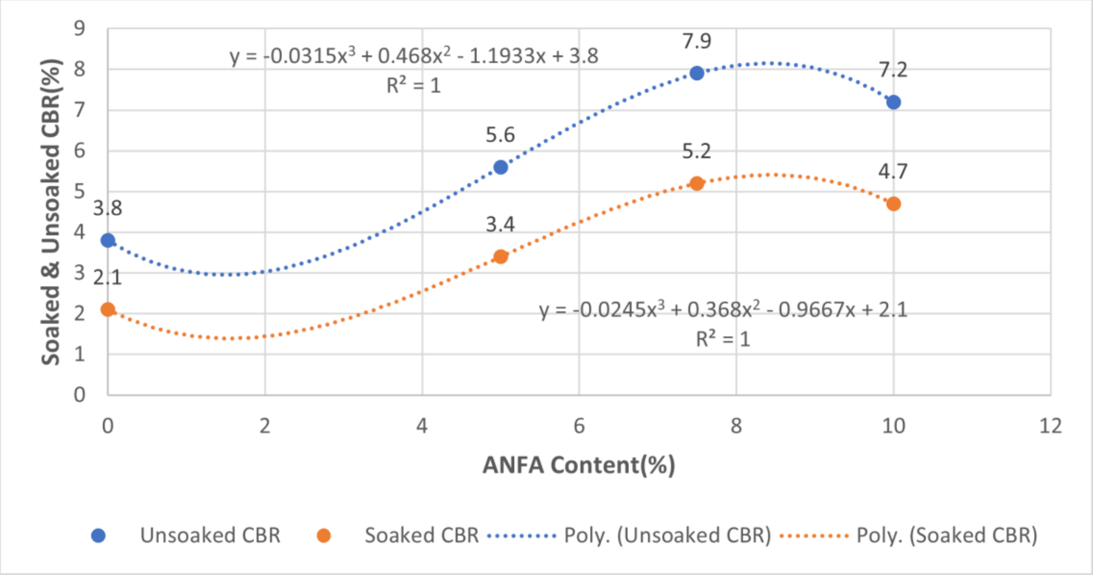

Figure 8 Variation of Soaked Unsoaked CBR with Areca Nut Fiber Ash Content.

IV. CONCLUSION

This study investigated the effectiveness of Areca Nut Fiber Ash (ANFA) combined with Ordinary Portland Cement (OPC) as a composite stabilizer for expansive clay soil from Allavaram, Andhra Pradesh, India. OPC was held constant at 2% by dry weight of soil in all treated mixes, while ANFA was varied at 5%, 7.5%, and 10%; the untreated control (M0) contained no admixtures. Laboratory tests conducted as per IS standards yielded the following principal conclusions:

1. The Differential Free Swell decreased substantially from 80% for untreated soil to 21% at 10% ANFA (a 73.75% reduction), confirming effective suppression of the montmorillonite swelling potential through cation exchange and pozzolanic gel encapsulation.
2. The Liquid Limit decreased from 70% to 57% while the Plastic Limit increased from 30.25% to 45.8%, producing a dramatic reduction in Plasticity Index from 39.75% to 11.2% at 10% ANFA, indicating markedly reduced susceptibility to shrink-swell behavior under seasonal moisture fluctuation.
3. Compaction characteristics exhibited a non-monotonic response with an optimum at 5% ANFA: the Optimum Moisture Content reached a minimum of 12.24% and the Maximum Dry Density a peak of 1.74 g/cc at this dosage (up from 18% OMC and 1.57 g/cc MDD for untreated soil), identifying 5% ANFA + 2% OPC as the most efficient mix for field compaction.
4. The unsoaked CBR increased from 3.8% for untreated soil to a peak of 7.9% at 7.5% ANFA content (a 108% gain), while soaked CBR improved from 2.1% to 5.2% at the same dosage (a 148% gain). The shared optimum at 7.5% under both moisture conditions identifies this as the most reliable mix for subgrade design, and the consistent improvement under soaked conditions confirms the durability of the stabilized matrix against moisture ingress.
5. The differential optimum behavior – compaction-optimal at 5% ANFA and strength-optimal at 7.5% ANFA – suggests that a dosage of 7.5% ANFA + 2% OPC provides the best overall balance between compaction efficiency, swelling suppression, plasticity reduction, and subgrade load-bearing capacity within the tested range.
6. ANFA, as a locally available agricultural by-product, presents a sustainable, cost-effective, and ecologically responsible alternative to conventional stabilizers, consistent with the principles of green geotechnical engineering.

Future investigations should incorporate Unconfined Compressive Strength (UCS) and extended curing period studies to comprehensively validate the long-term stabilization efficacy of the ANFA–OPC system.

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