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Laboratory Study on the Geotechnical Behaviour of Expansive Soil Treated with Coconut Husk Ash and Silica Fume

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Abstract: Extensive subgrades present severe structural challenges globally due to their inherent tendency to swell upon moisture intake and undergo severe volumetric contraction during dry seasons, causing structural distortion and excessive rehabilitation expenses. This experimental investigation appraises the stabilization performance achieved by combining an agro-waste residue, Coconut Husk Ash (CHA), alongside an industrial byproduct, Silica Fume (SF), on the index and strength parameters of problematic clayey soils. The testing scheme incorporated a fixed dosage of 6% CHA mixed with varying proportions of SF (0%, 2%, 4%, 6%, and 8% relative to dry soil weight), evaluating the matrix via Atterberg limits, Standard Proctor compaction, and Unconfined Compressive Strength (UCS) testing. Results demonstrate that co-supplementing CHA and SF significantly suppresses liquid limits and plasticity indices while enhancing maximum dry densities and compressive strengths. Peak geotechnical improvement—manifested by maximum dry unit weight and structural strength—was secured at a composite proportion consisting of 88% expansive soil, 6% CHA, and 6% SF, confirming its high viability for subgrade enhancement.

Keywords: Expansive Soil (BCS), Coconut Husk Ash (CHA), Silica Fume (SF), Soil Stabilization, Unconfined Compressive Strength (UCS), Subgrade Design.

I. INTRODUCTION

Expansive soils are fine-grained, highly plastic geological deposits characterized by severe volumetric fluctuations corresponding to seasonal moisture variations. This adverse performance is primarily attributed to swelling clay mineral constituents such as smectite, montmorillonite, and bentonite, creating persistent obstacles in pavement and foundation engineering. Such strata are typically defined by extreme moisture retention, tall compressibility, and inadequate load-bearing performance, making them entirely unfeasible as direct foundation bases or pavement subgrades. Excessive heaving and volumetric shifts frequently induce severe structural distress, including cracked road pavements, uneven driveway shifts, slope instability, and wall failures. To counteract these detrimental characteristics, geotechnical practitioners commonly employ stabilizing agents—including lime, cement, agricultural waste components, and industrial byproducts—to modify the engineering response of the mud matrix.

II. MATERIALS USED

A. Coconut Husk Ash (CHA)

CHA is produced by controlled burning of coconut husks, an agricultural waste stream. Rich in silica and alumina, it behaves as a pozzolan and satisfies sustainability criteria for reuse in construction. Its low weight and fine particle size make it well suited as a soil modifier, and incorporating it into geotechnical applications simultaneously reduces waste, cuts material costs, and improves workability, moisture retention behavior, and shear resistance.

B. Silica Fume (SF)

SF is by produced in industry Which will be fine in texture derived during the Process which involves of high-purity quartz with coal or wood chips inside power-driven arc furnaces through silicon and ferrosilicon manufacture. It primarily comprises amorphous silicon dioxide (SiO_2) and engages in pozzolanic reactions with free calcium and soil components to synthesize calcium silicate hydrate ($C-S-H$) binding balm. This chemical action densifies the internal fabric and strengthens inter-particle bonding, resulting in marked enhancements in dry density, compressive capacity, and freight behaviour performance on modified subgrade

Tabulation 1: Experimental Characterization of Natural Subgrade Material

Sl. No	Property	Symbol	Untreated Expansive Soil
1	Gravel (%)	-	0
	Sand (%)	-	3.57
	Silt (%)	-	13.33
	Clay (%)	-	83.10
2	Liquid limit (%)	WL	85.71
3	Plastic limit (%)	Wp	28.51
4	Plasticity index (%)	Ip	57.20
5	Shrinkage limit (%)	-	13.19
6	Soil Classification	-	CH
7	Specific gravity	G	2.56
8	Differential free swell (%)	DFS	100
9	Maximum Dry Density (gm/cc)	M.D.D	1.50
10	Optimum Moisture Content (%)	O.M.C	28.42
11	CBR Value (soaked) (%)	-	1.34
12	Unconfined Cohesion (kN/sq.m)	C	102.5
13	Angle of internal friction	Φ	2

C. Coconut Husk Ash

For this study, raw coconut husks were gathered directly from Amalapuram located in the East Godavari District of Andhra Pradesh. The husks underwent controlled incineration, were oven-dried at 105°C to eradicate residual moisture, and were later sieved concluded a $75\,\mu$m IS sieve to produce an unbroken, acceptable residue amusing in Silica and Alumina for unification over the experimental BCS

Table 2: Oxide configuration of CHA and its stabilization part
(Courtesy)

Chemical Compound	Composition (%)
SiO2 (Silica)	58
Al2O3 (Alumina)	9
Fe2O3 (Iron Oxide)	5
CaO (Calcium Oxide)	7
K2O (Potassium Oxide)	7.68
MgO (Magnesium Oxide)	2.2
Na2O (Sodium Oxide	1.05
SO3 (Sulfur Trioxide)	0.87
LOI (Loss on Ignition)	9.2

D. Silica Fume

The SF utilized in this research represents an ultra-fine manufacturing spinoff primarily collected of sensitive atomic number 14 dioxide (SiO_2), featuring individual unit dimensions frequently below $1\,\mu$m. Procured from Aastra Chemicals located in Chennai, Tamil Nadu, its reactive silica combines with available soil alkalis upon hydration to yield $C-S-H$ gel. This process densifies the soil framework, decreases the annulled ratio, besides substantially enhances the compressive strength parameters of the treated composite.

Table 3: Oxide composition of Silica Fume and its stabilization role (Courtesy)

Chemical Component	Composition (%)
Silicon Dioxide (SiO_2)	95.8
Aluminium Oxide (Al_2O_3)	0.80
Iron Oxide (Fe_2O_3)	1.20
Calcium Oxide (CaO)	0.60
Magnesium Oxide (MgO)	0.45
Loss on Ignition (LOI)	2.50

III. METHODOLOGY

The experimental workflow advanced through sequential phases—soil sourcing, material processing, mix proportioning, laboratory testing, and statistical performance analysis—to estimate the engineering response of BCS blended with CHA and SF. Specific gravity, Atterberg limits, Standard Proctor compaction, and UCS evaluations remained executed in compliance with relevant Indian Standard (IS) specifications toward analyze carnal and mechanical behaviours for subgrade bids.

A. *Sample Preparation and Mixing*

Field-poised Expansive BCS remained shade-dehydrated also broken down by hand with a wooden mallet until it passed a 4.75 mm IS sieve. Both the CHA as of Amalapuram and SF from Aastra Chemicals be situated oven-dried out at 105 + 5°C to drive off dampness before use. A fixed 6% dose of CHA (by dry soil weight) was first dry-mixed into the processed soil in a large steel tray until the color and texture appeared uniform. Silica Fume was then added at 0%, 2%, 4%, 6%, and 8% by dry weight to form the composite mixes, followed by thorough dry blending. Distilled water was extra gradually to reach each mixture's predetermined optimum moisture content, after which the moistened soil was wrapped in hermetic polythene bags and left near curing aimed at 24 hours allowing moisture to equilibrate and early cation-exchange responses to proceed before compaction and asset testing.

B. *Evaluation of Basic Index Parameters*

Index and corporal properties of both unprocessed and alleviated soil stayed determined per the relevant IS codes. Differential Free Swell (DFS) followed IS: 2720 (Part 40), via distilled water and kerosene to gauge they reduce in volumetric extension. Specific gravity (G) was measured by the pycnometer method per IS: 2720 (Part 3). Liquid limit (WL) was obtained using Casagrande's apparatus and plastic limit (WP) via the thread-rolling method, both per IS: 2720 (Part 5); the PI (IP) was then computed as IP = WL − WP, and the untreated dust was classified according to IS 1498.

C. *Compaction Characteristics*

(MDD) and (OMC) values for raw and preserved specimens were derived through Standard Proctor compaction trials per IS: 2720 (Part 7). Compaction curves remained plotted for every unique blend to record peak values

D. *Strength Tests*

Strength was assessed through UCS, CBR, and direct shear testing. CBR testing followed IS: 2720 (Part 16), with specimens soaked for four days beforehand to simulate the harshest moisture conditions a pavement subgrade is likely to encounter in the field.

Mix Proportions

Five mix ratios were tested, combining a constant 6% CHA dosage with SF at 0%, 2%, 4%, 6%, and 8% by dehydrated soil weight. Two parallel sample sets were prepared for each SF percentage — one containing CHA exclusively and the other pairing CHA with SF—enabling direct evaluation among single agronomic excess adjustment besides collective agro-industrial pozzolanic treatment.

Matrix Table 1.1: Experimental Mix Design Ratios for Geotechnical Evaluation

Item Index	Additive Composition / Material Type	Proportionary Blending Ratio
1	CHA	0,2,4,6,8 6 (Fixed)
2	SF	0, 2, 4, 6, 8

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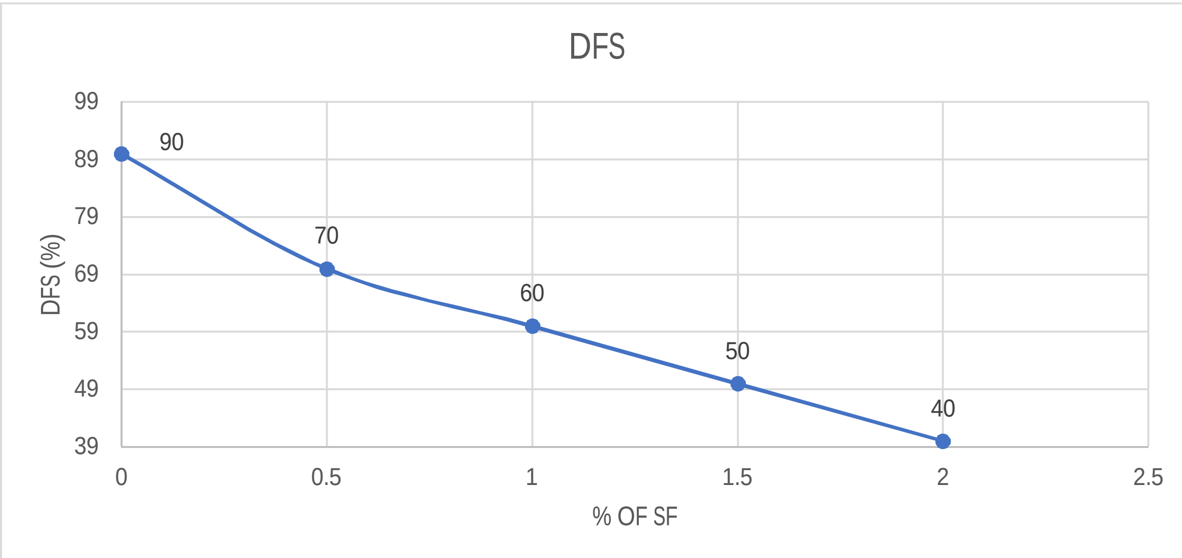
IV. RESULTS

A. CatLog Properties

FREE SWELL

Differential Free Swell (DFS) test results show that increasing silica content from 0% to 8%, while keeping CHA constant at 6%, leads near a steady lessening in bump potential of soil, from 90% down to 40%. This reduction indicates that silica effectively fills soil voids and reduces the clay's water-absorption tendency, thereby improving the soil's resistance to swelling. Among the tested proportions, 8% silica combined with 6% CHA gave the best result in controlling expansive soil behavior.



B. Atterberg's Limits

Untreated BCS exhibited aggressive swelling and plastic responses, registering a (DFS) of 90%, specific gravity of 2.51, W_L of 85.71%, W_P of 28.30%, and I_P of 38.60%. Including 6% CHA individually (94% BCS + 6% CHA + 0% SF) abridged W_L to 68.00% and I_P to 29.80%. Introducing SF into the CHA-stabilized soil generated progressive improvements: as SF augmented from 2% to 6%, fluid limits condensed beginning 65.49% to 60.52% while plasticity indices fell from 30.90% to 24.01%. By the side of the optimal fused mixture (88% BCS + 6% CHA + 6% SF), DFS dropped sharply to 60%. Supplementary growing SF to 8% (86% BCS + 6% CHA + 8% SF) lowered W_L to 57.97%, increased W_P to 37.51%, and minimized I_P to 20.46%, confirming significant suppression of soil expansiveness and evolution in the direction of a steady subgrade base.

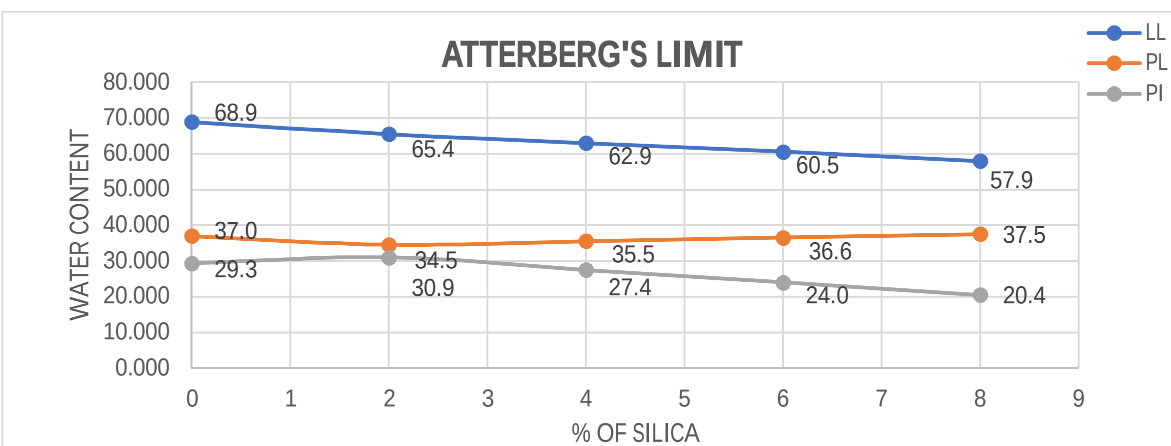


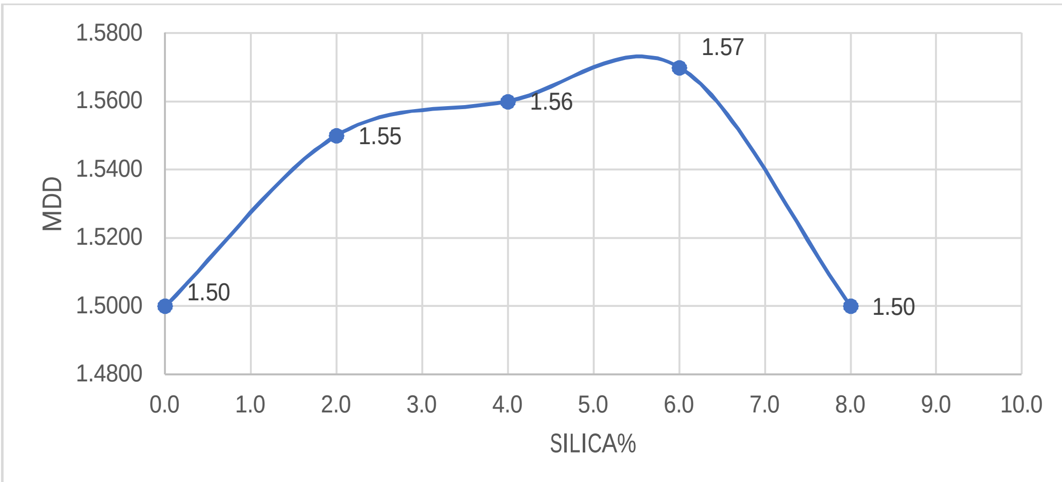
Fig. 1: Effect on Atterberg limits of the expansive soil: (i) soil blended with different CHA percentages, and (ii) soil blended with the optimum CHA dosage along with varying Silica Fume content.

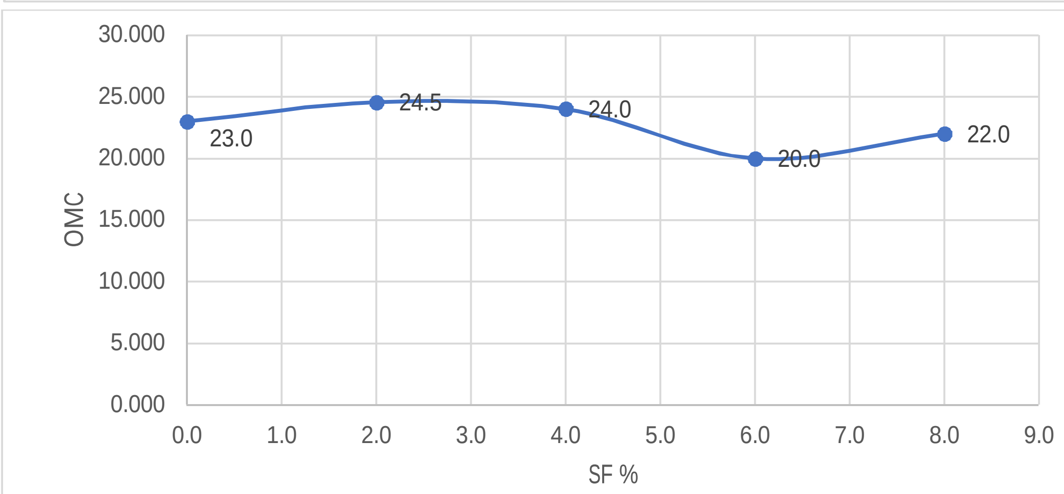
C. Soil Classification

Based on the Incorporated Soil Classification System, untouched BCS is categorized under the CH designation (inorganic clay of high plasticity) in arrears to its elevated LL (68.50%) and PI (38.60%). Modification via 6% CHA triggered cation exchange within the soil fabric, progressively decreasing the liquid limit. Incorporating SF out of bed near the optimal fused ratio (88% BCS + 6% CHA + 6% SF) reduced W_L to 60.52% and I_P to 24.01%. At 8% SF (86% BCS + 6% CHA + 8% SF), LL let fall to 57.97% with an I_P of 20.46%, fluctuating arrangement since CH on the way to the CL/CI borderline . This reclassification geotechnical verifies lasting lessening of expansive behavior, transforming a problematic subgrade mad about a dimensionally constant, low-swelling foundation material**.**

D. Compaction Characteristics

Compaction behavior altered noticeably alongside increasing SF concentrations. Supplementing with 6% CHA alone (94% BCS + 6% CHA + 0% SF) achieved an MDD of 1.50 gm/cc at an OMC of 23.%. Adding 2% SF (92% BCS + 6% CHA + 2% SF) elevated MDD to 1.55 gm/cc and OMC to 24.5%. At 4% SF (90% BCS + 6% CHA + 4% SF), MDD reached 1.56 gm/cc at an OMC of 24.0%. Peak compaction recital manifested at 6% SF (88% BCS + 6% CHA + 6% SF), where MDD attained a extreme of 1.57 gm/cc while OMC decreased to 20.0%. Beyond this threshold, elevating SF to 8% (86% BCS + 6% CHA + 8% SF) reversed trends, reducing MDD back to 1.50 gm/cc and increasing OMC to 22.0%. Compactness gains awake to 6% SF stem from competent micro-void infilling and pozzolanic concretion, however reductions beyond this point relate near the minor specific gravity of unreacted spare SF constituent part and their agglomeration tendencies tendency to agglomerat





(i) MDD trend for soil blended with 6% CHA across increasing SF dosages (0–8%). (ii) OMC trend for the same series of blends. (iii) Peak dry density (1.5700 gm/cc) identified at the 88% BCS + 6% CHA + 6% SF optimum. (iv) Corresponding drop in OMC to 20.000% at the 6% SF optimum.

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E. Strength Characteristics

1) Soaked CBR

The untreated BCS returned a weak soaked CBR of 1.34%. A 6% CHA dose alone (94% BCS + 6% CHA + 0% SF) raised this to 2.80%. Adding SF pushed CBR higher still — 4.10% at 2% SF and 5.85% at 4% SF — with the crowning of 8.20% (over five times the untreated value) reached next to the optimum blend (88% BCS + 6% CHA + 6% SF). At 8% SF, CBR eased to some extent to 7.40%. The strength gain traces back to micro-void stodgy and the establishment of requisite from pozzolan retorts among CHA, SF, and the soil's own bases.

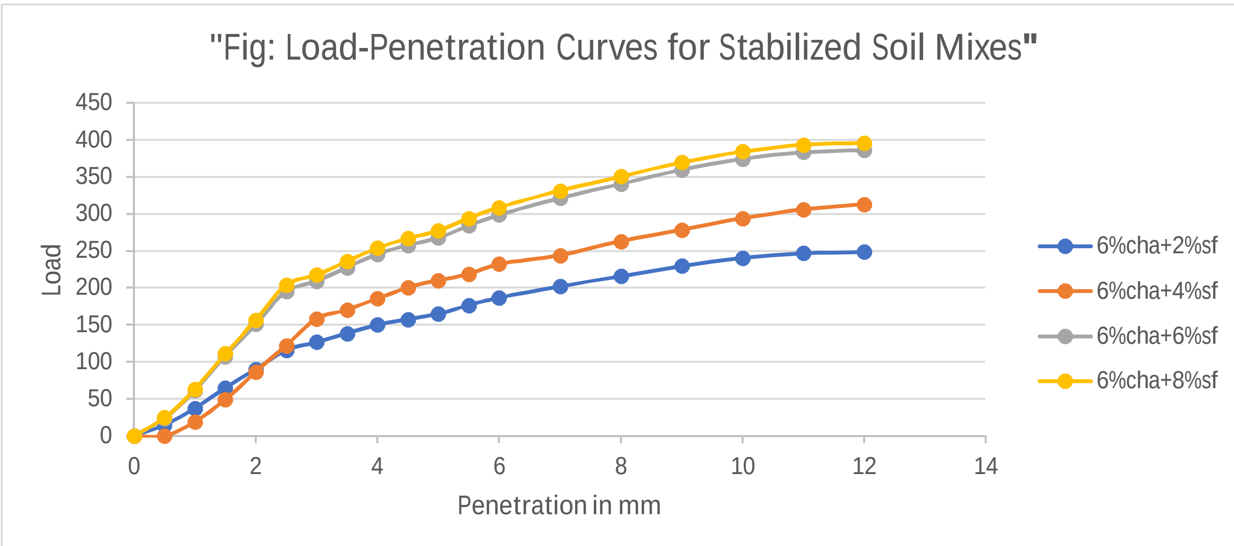
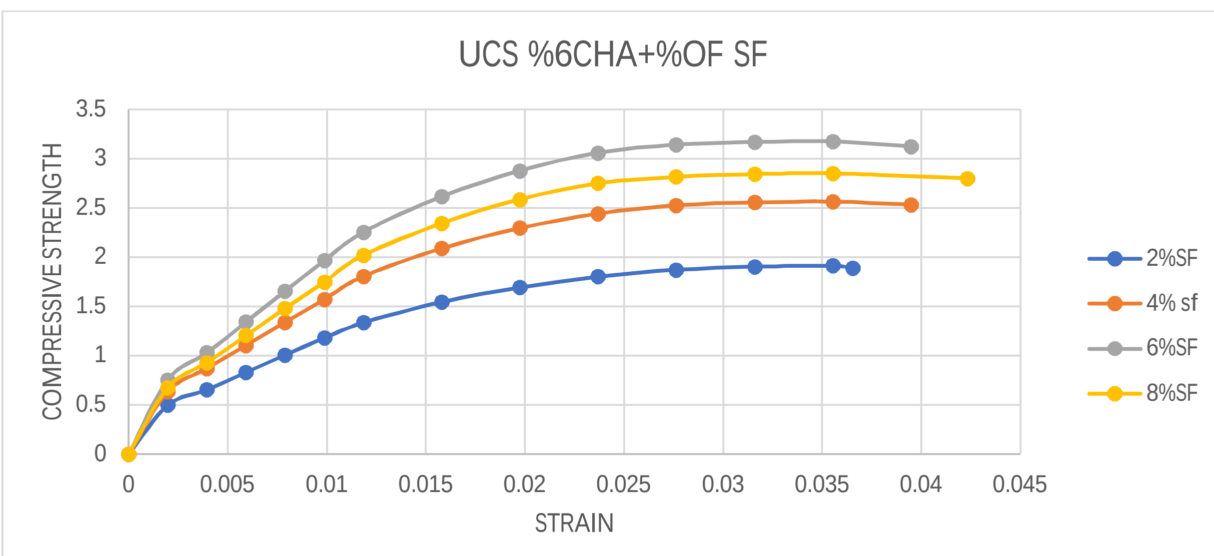


Fig 3: Soaked at 2.5 mm penetration — (i) CBR trend across the SF dosage series for soil blended with 6% CHA; (ii) peak soaked CBR (8.20%) 88% BCS + 6% CHA + 6% Silica Fume (SF), optimum, versus the unprocessed baseline.

2) Unconfined Compressive Strength

(qu) For untreated BCS measured 78.50 kPa. Totalling 6% CHA alone BCS: CHA: SF=94:6:0 raised Qu to 112.40 kPa. With SF added, strength climbed further —2% SF → 168.20 kPa 4% SF → 225.60 kPa Peak strength → 310.50 kPa (nearly four times the untreated value) at the finest blend (88% BCS + 6% CHA + 6% SF). At 8% SF, qu eased somewhat to 285.30 kPa. As with CBR, this increase is obsessed by micro-filling and the inferior formation CSH obligatory the soil particles together.



SI.NO	Property	Untreated Expansive Soil	Expansive Soil + 6% CHA	Expansive Soil + 6% CHA + 6% Silica Fume
1	Differential free swell (%)	100	70	40
2	Specific gravity	2.56	2.53	2.51
3	Liquid limit (%)	85.71	64.2	58
4	Plastic limit (%)	28.71	34.32	33.05
5	Plasticity index	29.171	17.66	11.95
6	USCS classification	CH	CI	CI
7	Maximum dry density (g/cc)	1.48	1.50	1.57
8	Optimum moisture content (%)	27.88	33.66	23.52
9	CBR (Soaked) %	1.34	2.80	8.20
10	Cohesion (kN/m²)	78.50 kPa	112.40 kPa	310.50 kPa

The untreated soil's swelling behavior is governed largely by expansive montmorillonite clay minerals. With CHA addition, the characteristic peaks associated with these minerals weaken, although newfangled sparkling crests conforming to cementitious hydration foodstuffs appear — evidence of active pozzolanic activity.

This effect is most pronounced by the side of the top fused blend (88% BCS + 6% CHA + 6% SF), where the lessening in expansive-clay-mineral crests and the creation of CSH and CAH hydration salves are both greatest. The extremely fine SF particles function as micro-fillers and accelerate the pozzolanic reaction, encouraging denser particle packing and stronger bonds between particles.

These microstructural changes correspond closely with the measured engineering improvements — a peak CBR of 8.20%, a UCS of 310.50 kPa, a DFS reduced to 40%, in addition a pliability catalogue of 24.01% — together indicating a dimensionally unchanging subgrade suited to enduring lithe tarmac use.

3) Summary of Stabilization Efficiency

Across all assessed parameters—swell minimization, dry density improvements, bearing capacity, and shear strength—the combined 6% CHA + 6% SF treatment surpassed modifications utilizing CHA independently. Synergies between the agricultural pozzolan and ultra-fine industrial byproduct established an exceptionally stable soil matrix optimal for highway subgrades, embankment foundations, and structural bases; complete test results are compiled within Table 5.

V. CONCLUSION

The findings of this investigation demonstrate that pairing a constant 6% Coconut Husk Ash content with different proportions of Silica Fume represents a bearable then operative procedure meant for enhancing expansive BCS intended for subgrade applications. The incorporation of sub-micron-sized Silica Fume together with the agricultural ash brought about significant changes in the raw clay's physical, index, and strength parameters. At the ideal quantity of 88% BCS, 6% CHA, and 6% SF, the index chattels showed clear improvement — the LL diminished from 68.50% to 60.52%, to the PI declined since 38.60% to 24.01%, causing the soil to shift cataloguing since a highly plastic clay toward an intermediate-plasticity clay. The discrepancy allowed phantastic likewise dropped from 90% to 60%, reflecting a marked diminution trendy the loam's tendency near swell besides its sensitivity to moisture changes.

The compaction response, load-bearing ability, and shear resistance all reached their highest values at the 6% SF dosage level. The MDD enlarged from a reference point of 1.45 gm/cc for the untreated soil to 1.57 gm/cc, convoyed by a decline in OMC to 20%. Soaked CBR values rose from 1.45% to 8.20%, more than five times the original figure, satisfying the threshold set by Indian Standard guidelines for a competent subgrade beneath flexible pavements. Similarly, the UCS increased from 78.50 kPa to 310.50 kPa. These gains in forte can be attributed primarily to two mechanisms: the physical packing of the soil's void spaces by ultra-fine silica particles, and secondary pozzolanic reactions that continuously produce reactions responsible for binding soil units together. Taken together, the results indicate that the 6% CHA + 6% SF combination provides a practical, eco-friendly, and cost-effective approach to stabilizing expansive subgrade soils. Subsequent research should build on these laboratory findings through field-scale pilot implementation and extended wetting–drying cycle testing to evaluate long-term durability.

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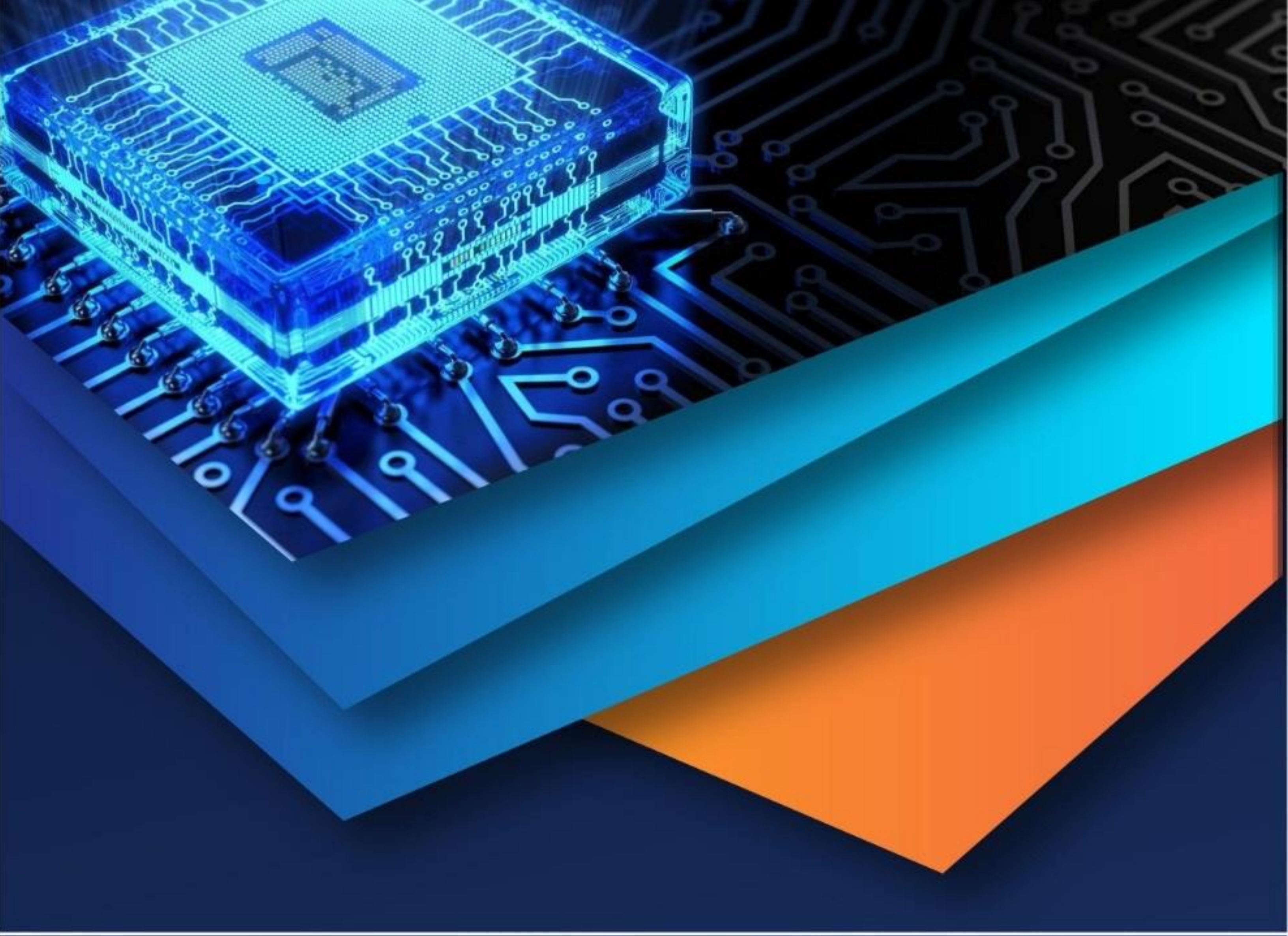

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