An Investigation on the Influence of Bagasse Ash and Zycobond on Improving the Strength Characteristics of Expansive Soil as Subgrade for Flexible Pavements Under Cyclic Pressures

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Abstract:- Expansive soils pose a serious threat to transportation infrastructure when used as pavement subgrade material. Because of their pronounced tendency to swell and shrink with changing moisture conditions, these soils give rise to differential settlement, surface cracking, heaving, rutting and premature deterioration of pavements. Such problems lower ride comfort, raise vehicle-operating costs, demand more frequent maintenance, disrupt traffic flow and shorten pavement service life, ultimately affecting both the economics and safety of road networks, particularly in regions that experience marked seasonal changes in moisture. In the present work, a highly expansive soil was stabilized using sugarcane bagasse ash (SBA) together with Zycobond, and the resulting improvement was assessed through geotechnical and microstructural testing. Untreated soil and soil treated with different proportions of SBA and Zycobond were examined in the laboratory to identify the optimum blend. The best performance was obtained with a combination of 20% SBA and 1.5% Zycobond. Under this treatment, the differential free swell fell from 110% to 20%, the liquid limit dropped from 66.51% to 52.00%, and the plasticity index reduced from 29.17% to 11.95%, shifting the soil classification from CH to CI. Maximum dry density rose from 1.588 to 1.780 g/cm³ while optimum moisture content fell from 27.88% to 16.82%. Soaked CBR values increased from 2.0% to 7.56%, pointing to a marked gain in bearing capacity. Results from cyclic plate load tests reinforced this trend, with the failure load rising from 900 kPa for the untreated soil to 2600 kPa for the stabilized blend, achieved at a lower settlement. X-ray diffraction (XRD) patterns showed a decline in expansive clay minerals and the appearance of stable cementitious phases, confirming that pozzolanic reactions were responsible for the observed gains in engineering behaviour. Overall, the combined use of SBA and Zycobond offers a sustainable, economical and environmentally sound approach for stabilizing expansive subgrade soils in pavement and foundation applications.

Keywords*: Expansive soil, Sugarcane bagasse ash, Zycobond, Soil stabilization, Differential free swell, California bearing ratio.*

1. Introduction

Expansive soils, commonly known as black cotton soils, are widely distributed across India and are characterized by high swell-shrink behavior due to the presence of montmorillonite clay minerals. Seasonal moisture fluctuations cause these soils to expand and contract, leading to differential settlement, pavement cracking, rutting, foundation damage, and increased maintenance costs. Although conventional stabilizers such as lime and cement improve soil properties, their environmental impact and high cost have encouraged the development of sustainable alternatives. Sugarcane bagasse ash (SBA), an agro-industrial by-product rich in reactive silica, has emerged as a promising eco-friendly stabilizing material because of its pozzolanic characteristics. Zycobond, a nano-polymer-based soil stabilizer, enhances interparticle bonding, reduces water penetration, and improves soil durability. The combined use of SBA and Zycobond is expected to provide superior stabilization through both chemical and physical mechanisms.

This study evaluates the stabilization of highly expansive soil using **20% SBA** and **1.5% Zycobond** through laboratory tests, including index properties, compaction characteristics, soaked California Bearing Ratio (CBR), cyclic plate load tests, and X-ray Diffraction (XRD) analysis.

The XRD analysis was conducted to investigate the mineralogical changes associated with stabilization. The untreated soil exhibited dominant expansive clay minerals responsible for high swelling and weak structural stability. After treatment, the intensity of expansive mineral peaks decreased, while new cementitious reaction products formed through the pozzolanic reaction between SBA and soil minerals. Zycobond further strengthened particle bonding, resulting in a denser and more stable soil matrix. These microstructural changes reduced swelling potential and improved the strength, stiffness, and load-bearing capacity of the stabilized soil. The study demonstrates that the combined application of SBA and Zycobond is an economical, sustainable, and effective solution for improving expansive soils in pavement and geotechnical engineering applications.

2. Materials used

The materials used in this research include locally available expansive soil, sugarcane bagasse ash (SBA), and Zycobond as a chemical stabilizer. All tests were conducted as per Indian Standard (IS) codes in a controlled laboratory environment.

2.1 Expansive Soil

Expansive soil was collected from **Rameswaram Village, Kakinada District, Andhra Pradesh, India**, at a depth of **1.0-1.5 m**. The soil was air-dried, pulverized, and sieved through a **425 µm IS sieve**. Classified as **CH (high plasticity clay)** under USCS, it exhibits high swelling, high plasticity, and low soaked bearing capacity, necessitating stabilization.

Table 1: Geotechnical properties of virgin expansive soil.

Sl.No	Properties		Symbol	Untreated Expansive soil
1	Soil Classification	Gravel (%)		0
		Sand (%)		5.44
		Silt (%)		26.52
		Clay (%)		68.04
2	Liquid limit (%)		W_L	66.511
3	Plastic limit (%)		W_p	37.34
4	Plasticity index (%)		I_p	29.171
5	Shrinkage limit (%)			12.28
6	Soil Classification			CH
7	Specific gravity		G	2.34
8	Differential free swell (%)		DFS	110
9	Maximum Dry Density (gm/cc)		M.D.D	1.588
10	Optimum Moisture Content (%)		O.M.C	27.88

11	CBR Value (soaked)(%)		1.63
12	Cohesion (kN/sq.m)	C	102.5
13	Angle of internal friction	Φ	2

2.2 Sugarcane Bagasse Ash (SBA)

Sugarcane bagasse ash is an agricultural waste derivative obtained from sugar mills after the burning of sugarcane bagasse for energy production. The collected ash was dried out in an oven at 105°C to remove moisture content and then sieved through a 75 µm IS sieve to obtain a fine, uniform material for mixing with soil. The sugarcane bagasse ash used in the present research was transported from **Nava Bharat Ventures Ltd (Sugar Division) located at Samalkot, East Godavari District.**

Table 2: Chemical composition of sugarcane bagasse ash

Chemical Compound	**Composition (%)**	**Role in Soil Stabilization**
SiO_2 (Silica)	58	Formation of Calcium Silicate Hydrate bonds
Al_2O_3 (Alumina)	9	Contributes to pozzolanic activity. Reacts with calcium to form CAH compounds
Fe_2O_3 (Iron Oxide)	5	Minor pozzolanic contributor to cementitious reactions
CaO (Calcium Oxide)	7	Provides some inherent cementing action; reacts with pozzolans in ash or soil.
K_2O (Potassium Oxide)	7.68	Alkali; can influence pH.
MgO (Magnesium Oxide)	2.2	Minor fluxing agent; participates in limited hydration reactions.
Na_2O (Sodium Oxide)	1.05	Alkali affects pore solution chemistry and may enhance early dissolution of silica.
SO_3 (Sulfur Trioxide)	0.87	Can influence ettringite formation in presence of lime; generally kept low to avoid expansion issues.
LOI (Loss on Ignition)	9.2	Represents unburned carbon and volatiles.

2.3 Zycobond

Zycobond is a exclusive nano-polymer-based soil stabilizer manufactured by **Zydex Industries, Gujarat, India**. It is a UV-stable, cross-linkable acrylic co-polymer emulsion with nano-sized particles (80-90 nm). This innovative stabilizer works through ion exchange and polymerization mechanisms, forming strong, flexible bonds between soil particles. It develops water resistance, reduces permeability, and improves the durability of stabilized soil without significantly disturbing the natural pH of the soil.

Table 3: Chemical composition of zycobond

Chemical Component	Composition (%)	Role in Soil Stabilization
Water	62.8	Acts as the carrier/solvent
Acrylic Co-polymer	34.2	**Primary active ingredient**. Nano-sized (80-90 nm) flexible polymer with high surface area. Chemically binds and conglomerates soil particles into a flexible cross-linked network.
Quaternary Ammonium Compounds	2.1	Helps in surface modification, stabilization of the emulsion, and may provide antimicrobial properties or enhanced adhesion to soil particles.
Acetic Acid	0.45	pH adjuster/stabilizer for the emulsion.
Methanol	0.116	helps in manufacturing and formulation stability.
Other Impurities	0.334	Minor additives for emulsion stability, UV/heat resistance, or performance enhancement.

3. Methodology

The investigational program was systematically designed to assess the efficiency of sugarcane bagasse ash (SBA) and Zycobond in stabilizing highly expansive soil. The study involved three soil mixtures: (i) untreated natural expansive soil, (ii) expansive soil stabilized with 20% sugarcane bagasse ash and (iii) expansive soil stabilized with 20% sugarcane bagasse ash + 1.5% Zycobond. All tests were conducted in accordance with the relevant Indian Standard (IS) codes of practices and ASTM standards.

3.1 Sample Preparation and Mixing

The collected expansive soil was air-dried, pulverized. Sugarcane bagasse ash was oven-dried at 105 ± 5°C before use. Zycobond was mixed with water

For the preparation of stabilized samples, the designed amount of bagasse ash (20% by dry weight of soil) was first carefully mixed with the dry soil in a large tray to achieve homogeneity. In the case of composite stabilization, the diluted Zycobond solution (1.5% by dry weight of soil) was progressively added to the soil-bagasse ash mixture and mixed carefully until a homogeneous blend was obtained. The samples were wrapped in airtight containers for 4days to allow proper reaction between the soil and stabilizers before testing.

3.2 Index Property Tests

Differential free swell (DFS) test was conducted as per IS: 2720 (Part 40) to measure the swell potential of the soil mixtures. Specific gravity was determined using the pycnometer method (IS: 2720 - Part 3). Atterberg limits (liquid limit and plastic limit) were determined using the Casagrande apparatus and rolling thread method respectively, as per IS: 2720 (Part 5). Plasticity index was calculated as the difference between liquid limit and plastic limit. The soil was classified according to the Unified Soil Classification System (USCS).

3.3 Compaction Characteristics

Standard Proctor compaction tests were carried out on untreated and treated soil mixtures as per IS: 2720 (Part 7) to determine the maximum dry density (MDD) and optimum moisture content (OMC). The compaction curves were plotted and the peak values were recorded.

3.4 Strength Tests

Unconfined compressive strength (UCS) tests and direct shear tests were performed to evaluate the shear strength parameters (cohesion and angle of internal friction). California Bearing Ratio (CBR) tests were conducted as per

IS: 2720 (Part 16) after 4 days of soaking to simulate worst-case field conditions for pavement subgrade applications.

3.5 Laboratory Cyclic Plate Load Test (CPLT)

The cyclic plate load test was conducted to evaluate the bearing capacity and deformation behavior of untreated and stabilized expansive soil under repeated loading. A 100 mm diameter rigid circular steel plate was placed on the prepared soil bed in a modal test tank. The load was applied incrementally using a hydraulic jack in multiple loading-unloading cycles up to the failure. Each cycle consisted of loading to the desired intensity followed by unloading to zero stress. Settlements were measured using two dial gauges placed diametrically opposite on the plate. Tests were performed as per relevant ASTM standards on untreated soil, 20% bagasse ash treated soil and soil treated with 20% bagasse ash + 1.5% Zycobond.

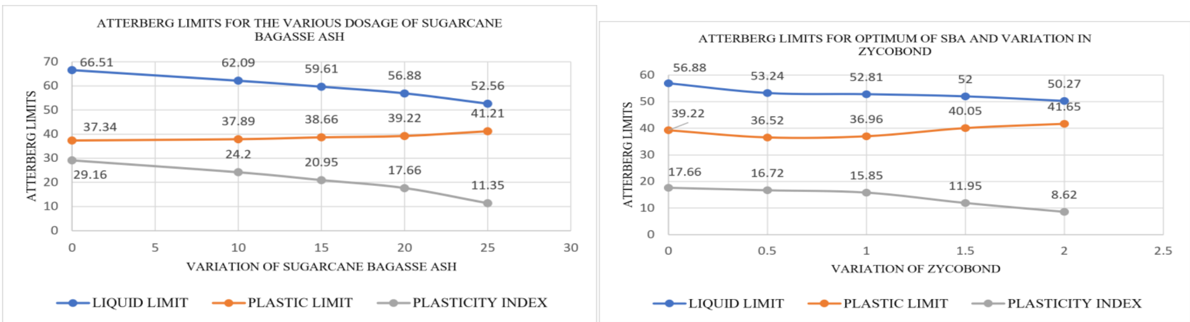
3.6 XRD analysis

X-ray diffraction (XRD) analysis was performed to investigate the mineralogical composition of untreated and stabilized expansive soil. The soil samples were oven-dried, pulverized, and sieved through the 75 µm sieve before testing. The analysis was carried out to examine the changes in mineralogy and the formation of cementitious reaction products resulting from the addition of sugarcane bagasse ash and Zycobond.

4. Results

The untreated expansive soil exhibited high swelling characteristics, with a differential free swell (DFS) of 110%, specific gravity of 2.34, liquid limit (LL) of 66.51%, plastic limit (PL) of 37.34%, and plasticity index (PI) of 29.16%. Stabilization with 20% sugarcane bagasse ash (SBA) reduced the DFS to 50% and PI to 17.66%, while increasing the specific gravity to 2.55. Further treatment with 20% SBA and 1.5% Zycobond reduced the DFS to 20% and PI to 11.95%, increased the specific gravity to 2.61, lowered the LL to 52.00%, and slightly increased the PL to 40.05%, indicating improvement in soil stability.

4.1 Index Properties



(i) (ii)

Fig 1: Atterberg limits of expansive soil (i) Treated with various dosage of Baggase as (ii) Treated with optimum of Baggase ash and various dosage of zycobond.

4.2 Soil Classification

According to the Unified Soil Classification System (USCS), the untreated expansive soil was classified as **CH** (high-plasticity clay), which is reliable with its elevated liquid limit and plasticity index. Ensuing treatment with 20% SBA as well as the collective SBA-Zycobond admixture, the classification shifted to **CI** (medium-plasticity clay). This reclassification is significant from a geotechnical perspective, as it indicates a fundamental enhancement in the plasticity characteristics of the soil, moving it away from the high-risk swelling category.

4.3 Compaction Characteristics

The maximum dry density (MDD) of the untreated expansive soil was 1.588 g/cc, which improved to 1.625 g/cc with 20% SBA and further to 1.780 g/cc with the combined 20% SBA + 1.5% Zycobond treatment. The optimum moisture content (OMC) correspondingly decreased from 27.88% in the untreated soil to 19.66% and 16.82% in the treated specimens. The synchronized increase in MDD and decrease in OMC is indicative of improved particle packing and densification helped by the cementitious compounds formed through pozzolanic reactions between SBA and the calcium ions present in the soil, further amplified by the Zycobond polymer network.

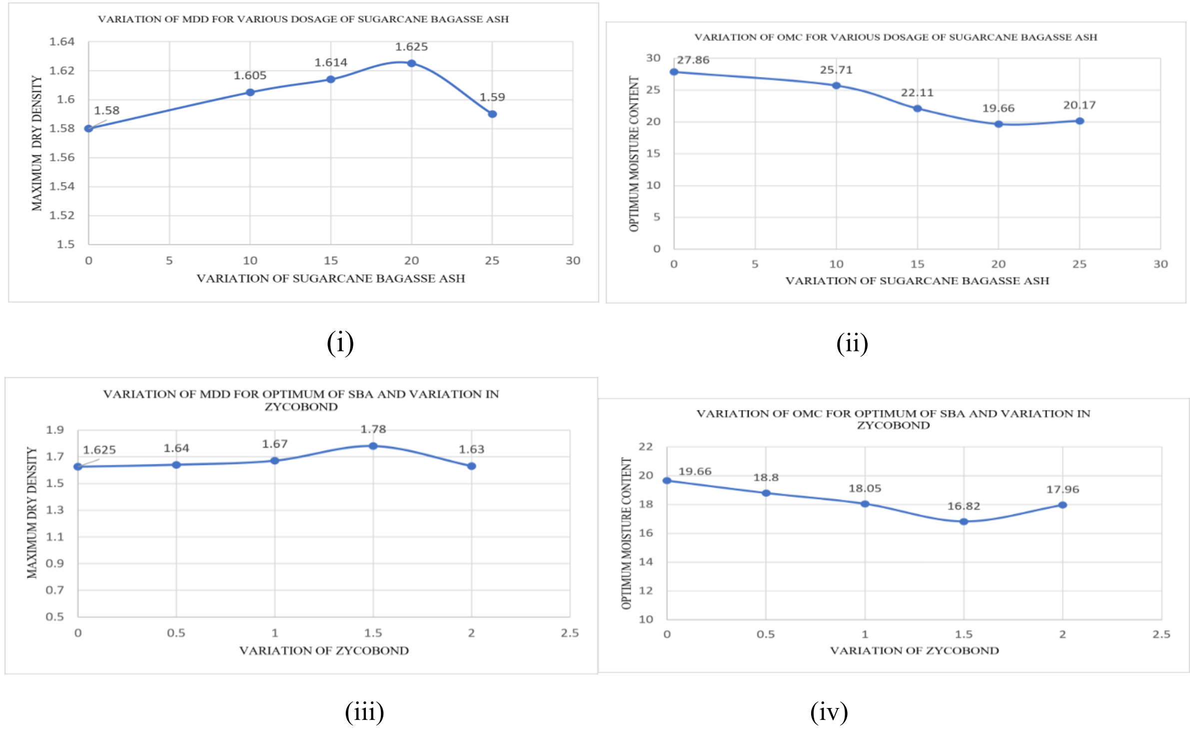


Fig 2: compaction characteristics (i)variation of maximum dry density for various dosage of bagasse ash (ii) variation of optimum moisture content for various dosage of bagasse ash (iii) variation of maximum dry density for optimum of bagasse ash and various dosage of zycobond. (iv) variation of optimum moisture content for optimum of bagasse ash and various dosage of zycobond.

4.4 Strength Characteristics

4.4.1 Soaked CBR

The soaked California Bearing Ratio (CBR) of the untreated expansive soil was recorded at a mere 1.63%, categorizing it as a very poor subgrade material. The addition of 20% SBA pointedly improved the soaked CBR to 4.78%, representing a nearly threefold increase. The inclusion of 1.5% Zycobond in conjunction with 20% SBA yielded a soaked CBR of 7.56%. This substantial enhancement in bearing capacity can be attributed to the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gel phases resultant from pozzolanic activity, mutual with the polymer-induced interparticle bonding effect of Zycobond.

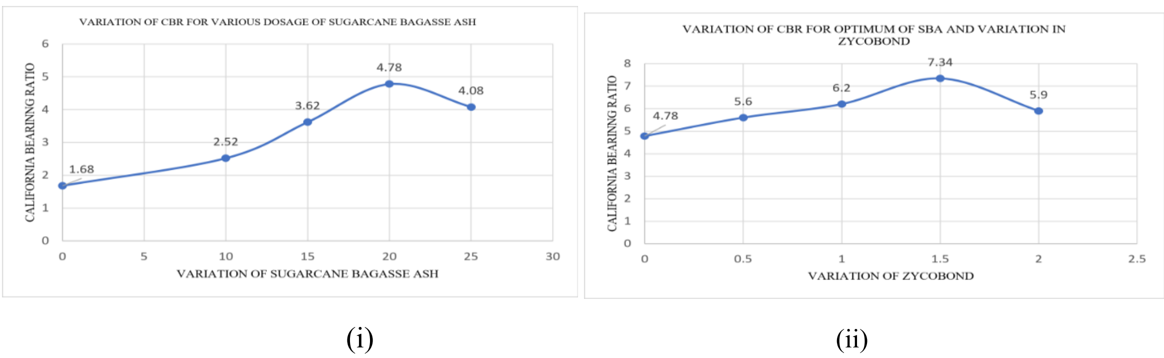


Fig 3: CBR at 2.5 mm penetration (i) variation of CBR for various dosage of bagasse ash (ii) variation of CBR for optimum of bagasse ash and various dosage of zycobond.

4.4.2 Shear Strength Parameters

The angle of internal friction (φ) of the untreated expansive soil was 2°, increasing to 3.95° with 20% SBA treatment and to 4.75° with the united admixture. Cohesion (c) values showed a decreasing trend, from 102.5 kPa in the untreated soil to 96.56 kPa (20% SBA) and 92.6 kPa (20% SBA + 1.5% Zycobond). The diminution in cohesion is consistent with the replacement of clayey fines by coarser pozzolanic particles, which condenses the dominance of surface cohesion while refining frictional resistance. The global shear behaviour indicates a transition from a predominantly cohesive failure mechanism in the untreated soil toward a more frictional one in the stabilized varieties, which is generally favourable for subgrade and foundation applications.

Table 4: composite geotechnical properties of treated and untreated expansive soil

Sl. No	Property	Untreated expansive soil	Expansive soil + 20% SBA	Expansive soil + 20% SBA + 1.5% Zycobond
1	Differential free swell (%)	110	50	20
2	Specific gravity	2.34	2.55	2.61
3	Liquid limit (%)	66.511	56.88	52
4	Plastic limit (%)	37.34	39.22	40.05
5	Plasticity index	29.171	17.66	11.95
6	USCS classification	CH	CI	CI
7	Maximum dry density (g/cc)	1.588	1.625	1.78
8	Optimum moisture content (%)	27.88	19.66	16.82
9	CBR (%)	1.63	4.78	7.56
10	Angle of internal friction	2	3.95	4.75
11	Cohesion (KN/m^2)	102.5	96.56	92.6

4.4.3 Cyclic plate load test (CPLT)

The cyclic plate load test demonstrated significant improvement in the bearing capacity and stiffness of expansive soil after stabilization. The untreated soil failed at **900 kPa** with a settlement of **2.49 mm**. Stabilization with **20% sugarcane bagasse ash (SBA)** increased the failure load to **1600 kPa** with a settlement of **2.285 mm**. The optimum combination of **20% SBA + 1.5% Zycobond** achieved the highest performance, sustaining **2600 kPa** (a **189% increase** over untreated soil) at a reduced settlement of **1.875 mm**, confirming its superior load-bearing capacity and deformation resistance for pavement and foundation applications.

Table 5: load carrying capacity and deformation resistance of treated and untreated expansive soil

Treatment	**Failure Load (KPa)**	**Settlement at Failure (mm)**	**Load Improvement**	**Settlement Reduction**
Untreated	900	2.49	-	-
20% Sugarcane Bagasse Ash	1,600	2.285	**+78%**	**8.2%**

20% Bagasse Ash + 1.5% Zycobond	**2,600**	**1.875**	**+189%**	**24.7%**

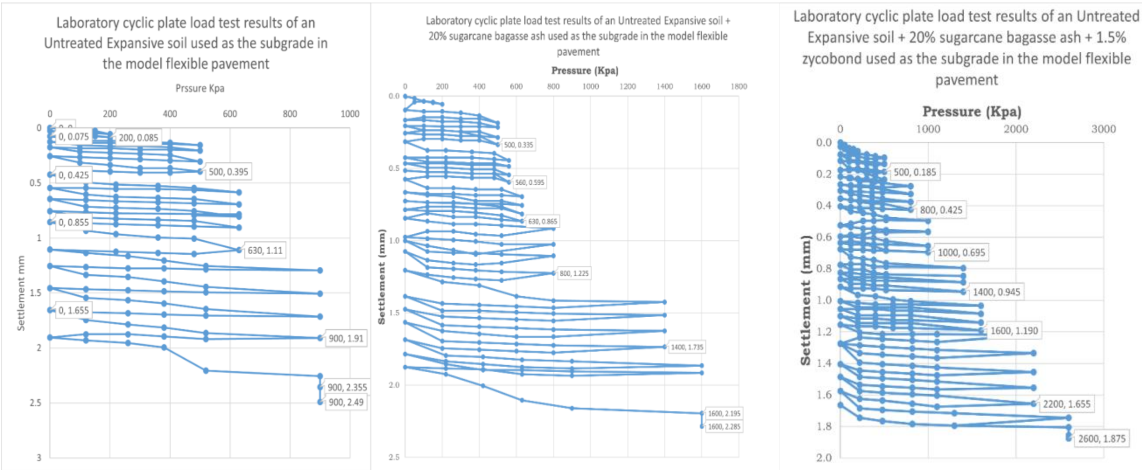
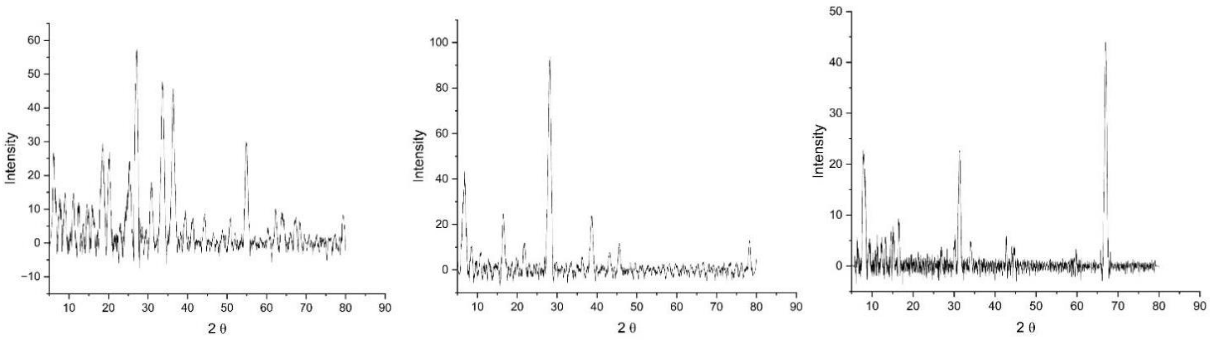


Fig 4: Cyclic plate load test (a) Expansive Soil (b) Expansive Soil + 20% of Sugarcane Bagasse Ash (c) Expansive Soil + 20% of Sugarcane Bagasse Ash + 1.5% Zycobond.

4.6 Microstructural analysis (XRD Analysis)



(a) (b) (c)

Fig 5: Microstructural analysis (XRD) (a) Expansive Soil (b) Expansive Soil + 20% of Sugarcane Bagasse Ash (c) Expansive Soil + 20% of Sugarcane Bagasse Ash + 1.5% Zycobond.

The untreated soil contains dominant expansive clay minerals responsible for high swelling behavior. Upon addition of SBA, the intensity of clay mineral peaks decreases while new peaks associated with cementitious hydration products emerge, confirming the occurrence of pozzolanic reactions.

The combined use of SBA and Zycobond results in the greatest reduction of expansive clay minerals and the strongest development of hydration products. The polymeric action of Zycobond enhances particle aggregation and facilitates stronger interparticle bonding, promoting a denser and more stable microstructure.

These mineralogical transformations correlate well with the observed improvements in engineering properties, including increased California Bearing Ratio (CBR), reduced differential free swell (DFS), decreased plasticity, improved shear strength, and enhanced pavement performance.

4.5 Summary of Stabilization Efficacy

The combined treatment of 20% SBA and 1.5% Zycobond outperformed SBA alone by reducing swell potential, improving density, bearing capacity, and plasticity. The synergistic action of SBA and Zycobond produced a more stable soil suitable for highway subgrades and engineered fill. The corresponding results are presented in Table.

5. Conclusion

This study demonstrated that the combined use of **20% sugarcane bagasse ash (SBA)** and **1.5% Zycobond** is an effective and sustainable stabilization technique for improving the expansive soils. Significantly, the optimum combination improved the engineering behavior of the expansive soil by reducing the differential free swell index from **110% to 20%**, lowering the liquid limit from **66.51% to 52%** and the plasticity index from **29.17% to 11.95%**, thereby changing the soil classification from **CH** to **CI**. Compaction characteristics also improved with the maximum dry density increasing from **1.588 g/cc to 1.78 g/cc** and the optimum moisture content decreasing from **27.88% to 16.82%**. The soaked CBR increased from **2% to 7.56%**, indicating a substantial improvement in strength and load carrying capacity.

Further the effectiveness of stabilization was confirmed by cyclic plate load test. The untreated soil failed at **900 kPa** with **2.49 mm** settlement, whereas the stabilized soil sustained upto **2600 kPa** at a reduced settlement of **1.875 mm**, demonstrating significantly higher stiffness and resistance to repeated loading.

The XRD (X-ray Diffraction) analysis supported these improvements by revealing microstructural changes after stabilization. The untreated soil exhibited dominant expansive clay minerals with weak cementation, whereas the treated soil showed a reduction in expansive mineral peaks and the formation of stable cementitious products through pozzolanic reactions between SBA and soil minerals. Zycobond enhanced the particle bonding, resulting in a denser and more compact soil matrix, which has contributed to reduced swelling and increased strength.

Conclusively, the combined SBA-Zycobond stabilization method provided a cost-effective, eco-friendly and sustainable solution for improving expansive soils. Future studies should focus on long-term durability and field-scale validation under varying environmental and loading conditions.

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