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Stabilization of Expansive Soil by Using with Coffee Powder and Fly Ash

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***Abstract* - Expansive soils exhibit significant swelling and shrinkage behavior due to moisture variation, causing serious problems in pavements, foundations, and other civil engineering structures. Stabilization of such soils using sustainable waste materials has gained significance in recent years. In the present study, Coffee Powder (CP) and Fly Ash (FA) were used as eco-friendly stabilizing materials to improve the engineering properties of an expansive soil collected from Gujalamandyam, Tirupati, Andhra Pradesh. Laboratory investigations were carried out using varying percentages of Coffee Powder (2%, 5%, 10%, and 15%) and Fly Ash (5%, 10%, 15%, and 20%). Standard Proctor compaction, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), X-Ray Diffraction (XRD), and Energy Dispersive Spectroscopy (EDS) tests were conducted. The results indicated better behaviour with combined mix of (5% CP + 5% FA) exhibiting the highest UCS value of 760.88 kPa at 7 days curing, along with considerable improvement in CBR values. The study demonstrates that Coffee Powder and Fly Ash can be effectively utilized for sustainable expansive soil stabilization.**

Keywords: Expansive Soil; Coffee Powder; Fly Ash; Soil Stabilization; Unconfined Compressive Strength (UCS).

I. INTRODUCTION

Soil is one of the most important natural materials used in civil engineering construction, as it forms the foundation for structures such as buildings, highways, embankments, retaining walls, and pavements. The stability and durability of any structure primarily depend on the engineering properties of the underlying soil. However, certain soils possess undesirable characteristics that adversely affect structural performance. Among them, expansive soil is considered one of the most problematic soils because of its tendency to undergo excessive swelling during wet conditions and shrinkage during dry conditions [1]. These volume changes result in differential settlement, pavement cracking, heaving of foundations, and structural distress, leading to increased maintenance and repair costs.

Expansive soils are generally rich in clay minerals such as Montmorillonite, which absorb water and expand significantly. In many parts of India, especially in semi-arid regions, expansive soils are widely distributed and pose major challenges for infrastructure development. Therefore, improving the engineering behavior of expansive soil through stabilization techniques has become essential in geotechnical engineering applications.

Traditionally, chemical stabilizers such as Lime and Cement have been extensively used to improve soil properties. Although these materials effectively enhance soil strength and reduce plasticity, their large-scale usage contributes to environmental pollution and increases construction costs due to high energy consumption during production. In recent years, researchers have focused on utilizing industrial by-products and agricultural waste materials as sustainable alternatives for soil stabilization. These waste materials not only improve soil properties but also help in waste management and environmental protection.

Coffee Powder (CP) is an organic waste material generated in significant quantities from households, restaurants, hotels, and coffee-processing industries. Disposal of spent coffee waste creates environmental concerns because of its biodegradable nature and large accumulation in landfills. Due to its fibrous texture and water absorption characteristics, coffee powder has recently gained attention as a potential stabilizing material for expansive soils [4]. The addition of (CP) can improve particle bonding, reduce shrinkage cracks, and modify the compaction characteristics of soil.

Fly Ash is a fine powdery by-product obtained from coal combustion in thermal power plants. It contains Silica, Alumina, and Calcium compounds that exhibit pozzolanic properties in the presence of moisture. Because of its

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cementitious behavior, FA has been widely used in pavement construction, embankments, and soil stabilization works [5]. The utilization of FA not only improves the strength and bearing capacity of soil but also reduces environmental pollution associated with industrial waste disposal.

In the present study, expansive soil collected from Gujalamandyam, Tirupati, Andhra Pradesh, was stabilized using CP and FA in varying proportions. Laboratory tests for Compaction characteristics, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), Microstructural studies using Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and Energy Dispersive Spectroscopy (EDS) were conducted to evaluate the influence of these stabilizers on soil properties. The primary objective of this study is to investigate the effectiveness of Coffee Powder and Fly Ash, individually and in combination form, for improving the strength, and Swelling tendency of expansive soil. The study also emphasizes sustainable utilization of waste materials for eco-friendly ground improvement applications.

II. MATERIALS USED

The materials used in the present investigation include expansive soil, Coffee Powder, and Fly Ash. The properties of these materials significantly influence the behavior and performance of stabilized soil mixtures. Laboratory tests were conducted to determine the physical and engineering properties of the collected soil before and after stabilization.

2.1 Expansive Soil

The expansive soil used in this study was collected from Gujalamandyam, Tirupati, Andhra Pradesh, at a depth of approximately 2 m below the ground surface in order to ensure uniform nature of Soil. The collected soil sample was air-dried, pulverized manually, and sieved through a 4.75 mm IS sieve to remove oversized particles before testing.

Figure 1: Collected Expansive Soil Sample

Soil sample collected location

Coffee Powder (CP) waste used in the study was collected from Aroma Coffee House located in Tirupati, Andhra Pradesh. The collected coffee waste was dried under sunlight to remove moisture and then ground into fine powder form before mixing with soil. Coffee Powder is an organic waste material generated after coffee preparation and is generally disposed of as landfill waste. The utilization of Coffee Powder in soil stabilization provides an environmentally sustainable solution for waste management.

The fibrous and porous nature of CP improves particle interlocking and water absorption behavior in soil mixtures. In the present investigation, CP was added to expansive soil in varying proportions of 2%, 5%, 10%, and 15% by dry weight of soil.

Figure 2: Coffee Powder used for Stabilization

2.2 Fly Ash

Fly Ash (FA) used in the study was collected from a road construction site near Upperpalli, Tirupati, Andhra Pradesh. FA is a fine powdery by-product obtained from coal combustion in thermal power plants. It contains Silica, Alumina, Calcium Oxide, and other reactive compounds that exhibit pozzolanic behavior in the presence of moisture.

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FP enhance formation of concentrations compounds as per literature review. In this study, FA was mixed with soil at proportions of 5%, 10%, 15%, and 20% by dry weight of soil.

Figure 3: Fly Ash used for stabilization

III. EXPERIMENTAL PROGRAMME

3.1 Tests on Untreated Soil

The engineering properties of untreated soil were determined using standard laboratory tests such as Grain Size Analysis, Atterberg Limits, Specific Gravity, Free Swell Index, Compaction characteristics, UCS, and CBR. The soil exhibited high Liquid Limit and Free Swell Index, indicating significant degree of swelling.

Table 1 presents the engineering properties of selected expansive soil obtained through laboratory testing according to relevant Indian Standard (IS) codes.

Table 1: Properties of Untreated Expansive Soil

S. No	Property	Values	Reference
1	Grain size Analysis		IS: 2720(Part 4), 1985
	Gravel (%)	0.0	
	Sand (%)	40.6%	
	Silt+ Clay (%)	59.4%	
2	Specific Gravity (G)		IS: 2720(Part3) sec 1,1980
	Coarse Fraction	2.6	
	Fine Fraction	2.7	
	Total Soil	2.65	
3	Atterberg Limits		IS: 2720(Part5),1985
	Liquid Limit (%)	68.6%	
	Plastic Limit (%)	43.1%	
	Plasticity Index	25.5%	
4	I.S. Classification	CH (Inorganic clay of High Plasticity)	IS: 1498
5	Free Swell Index (%)	170.0%	IS: 2720(Part40),1977
6	Compaction characteristics (H.C)		IS: 2720(Part8),1980
	Maximum Dry Density (MDD) (kN/m3)	19.10	
	Optimum Moisture Content (OMC) (%)	12.7%	
7	Unconfined Compression Strength (kPa)	195.55	IS: 2720(Part10),1991
8	Californian Bearing Ratio (CBR)		IS: 2720(Part16), 1987
	Unsoaked (%)	12.8	
	Soaked (%)	9.1	

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The high Liquid Limit, Plasticity Index, and Free Swell Index confirm the expansive nature of the soil. The low making the soil unsuitable for direct use in pavement and foundation applications without stabilization.

The experimental investigation was carried out to evaluate the effectiveness of Coffee Powder (CP) and Fly Ash (FA) in improving the strength and reducing Swelling tendency of expansive soil. Laboratory tests were conducted on plain soil and (soil – Admixtures) with varying percentages of additives. The methodology adopted in the present study included material preparation, mix proportioning, sample preparation, curing, and laboratory testing.

3.2 Mix Proportions

CP and FA were mixed separately with expansive soil in different proportions by dry weight of soil. CP was added at 2%, 5%, 10%, and 15%, while FA was added at 5%, 10%, 15%, and 20%. Based on the strength performance obtained from laboratory testing, optimum proportions were selected for preparing combined mixes.

Table 2: Mix Designations for (Soil–CP) Mixtures

Mix Designation	Coffee Powder (%)	Proportion
C1	0	100% Soil
C2	2	Soil + 2% CP
C3	5	Soil + 5% CP
C4	10	Soil + 10% CP
C5	15	Soil + 15% CP

Table 3: Mix Designations for (Soil–FA) Mixtures

Mix Designation	Fly Ash (%)	Proportion
F1	0	100% Soil
F2	5	Soil + 5% FA
F3	10	Soil + 10% FA
F4	15	Soil + 15% FA
F5	20	Soil + 20% FA

The optimum values of admixture is based on maximum then combination (CP and FA) obtained UCS value was fixed for further investigation.

3.3 Sample Preparation

The collected expansive soil was air-dried and pulverised manually before passing through a 4.75 mm IS sieve. CP and FA were separately dried to remove moisture and then mixed thoroughly with soil in predetermined proportions to obtain uniform mixtures. Water corresponding to Optimum Moisture Content (OMC) was added gradually during mixing to ensure proper consistency and homogeneity.

Compacted specimens at OMC and MDD for UCS were extracted and Soil was compacted OMC and MDD CBR tests. Cylindrical specimens were prepared for UCS testing, while CBR moulds were used for soaked and unsoaked CBR tests.

3.4 Laboratory Tests Conducted

The following laboratory tests were conducted on selected soil according to Indian Standard (IS) codes:

- Grain Size Analysis – IS:2720 (Part 4)
- Specific Gravity Test – IS:2720 (Part 3)
- Atterberg Limits Test – IS:2720 (Part 5)
- Free Swell Index Test – IS:2720 (Part 40)
- Standard Proctor Compaction Test – IS:2720 (Part 8)
- Unconfined Compressive Strength (UCS) Test – IS:2720 (Part 10)

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- California Bearing Ratio (CBR) Test – IS:2720 (Part 16)

Compaction characteristics, UCS, CBR tests were conducted as per the above procedures for on plain Soil and (Soil- CP) mixes, (Soil – FA) mixes and (Soil – CP – FA) mixes at optimum percentage.

Curing Procedure

Prepared UCS and CBR specimens were cured for periods of 0, 3, 7 days under controlled laboratory conditions. The specimens were sealed properly to maintain moisture content during curing. After completion of the curing period, the specimens were tested to determine strength improvement with time.

IV. RESULTS AND DISCUSSION

The results obtained from laboratory investigations on untreated and stabilised expansive soil are presented and discussed in this section. The influence of coffee powder (CP) and fly ash (FA) on compaction characteristics, strength behaviour, of expansive soil was evaluated through Standard Proctor compaction, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR).

4.1 Compaction Characteristics

The compaction characteristics of soil mixed with varying percentages of CP and FA were determined using the Standard Proctor Test. The variations in Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for soil–CP mixtures are presented in Table 4.

Table 4: Compaction Characteristics of (Soil–CP) Mixtures

Mix	OMC (%)	MDD (kN/m³)
C1	12.7	19.10
C2	13.8	20.10
C3	14.9	21.20
C4	14.3	19.60
C5	13.9	18.40

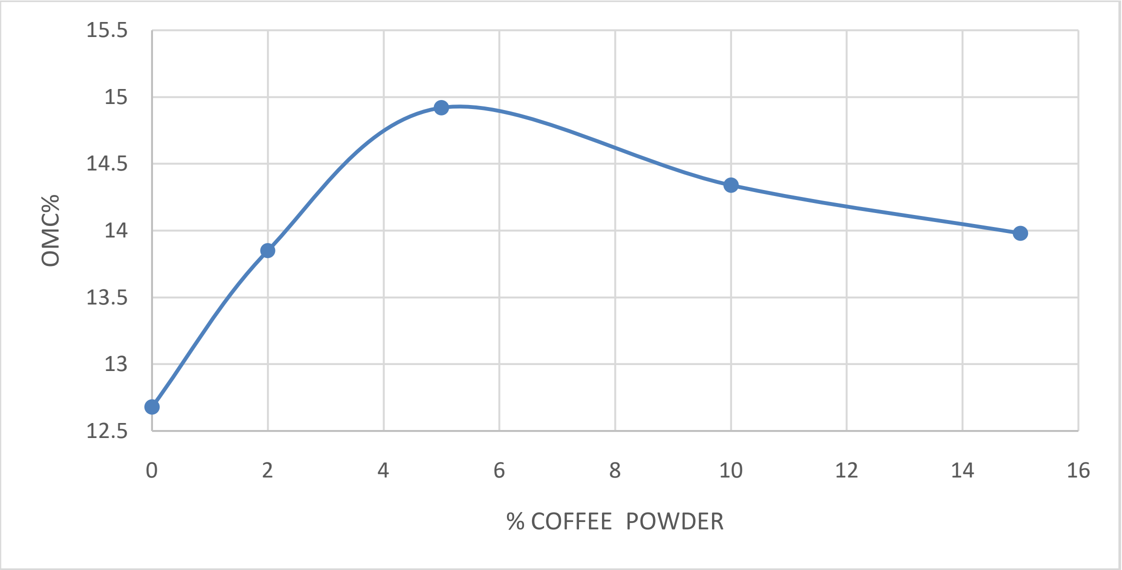

Figure 4: Variation of OMC of (Soil- CP) Mixes

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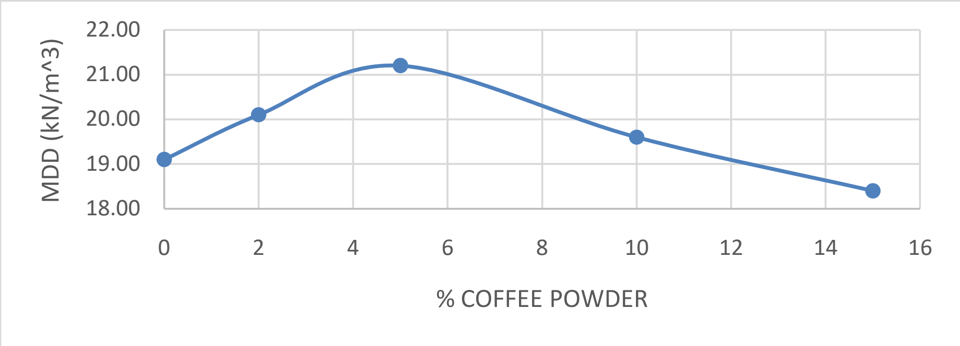

Figure 5: Variation of MDD of (Soil- CP) Mixes

From the above graph it can be observed the OMC increases with the addition of CP up to 5% due to the water absorption capacity and porous nature of coffee particles. The MDD increased from 19.10 kN/m³ for plain soil to 21.20 kN/m³ at 5% CP, indicating improved particle packing and compaction efficiency. Beyond 5% CP, the MDD decreased because excess coffee powder increased the void ratio and reduced inter-particle bonding.

Table 5: Compaction Characteristics of (Soil–FA) Mixtures

Mix	OMC (%)	MDD (kN/m³)
F1	12.68	19.10
F2	13.12	19.80
F3	12.21	18.60
F4	12.03	18.40
F5	11.88	18.20

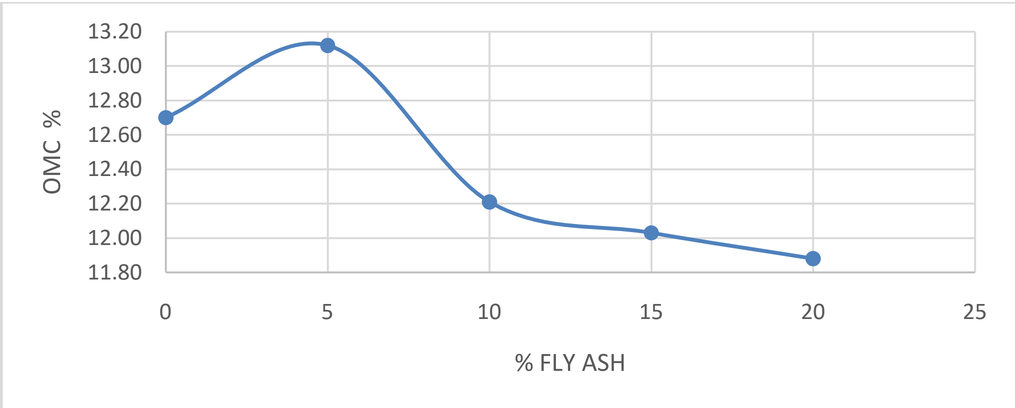

Figure 6: Variation of OMC of (Soil- FA) Mixes

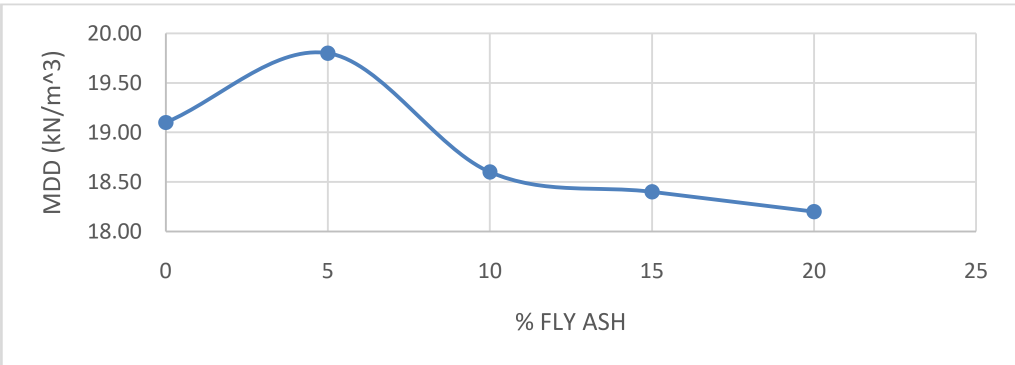

Figure 7: Variation of MDD of (Soil- FA) Mixes

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From the above graphs it can be observed that the addition of FA slightly increases the MDD at 5% FA due to better gradation and filling of voids within soil particles. However, a further increase in fly ash content reduced MDD because of the lower Specific Gravity of FA. The OMC decreases gradually with increasing FA content, indicating reduced water demand during compaction.

4.2 Unconfined Compressive Strength (UCS)

The UCS tests were conducted on plain soil, (Soil – CP) mixes and (Soil – FA) mixes and stabilised soil specimens cured for 0, 3, 7, and 14 days to evaluate strength improvement due to stabilisation. Table 6 presents the UCS values of Soil (Soil – CP) mixes and (Soil – FA) mixes.

Table 6: UCS Values of (Soil–CP) Mixtures

MIX	0 Days	3 Days	7 Days	14 Days
C1	195.55	195.55	195.55	195.55
C2	248.40	286.75	462.80	428.40
C3	310.88	363.25	574.70	516.12
C4	276.30	322.40	510.80	458.50
C5	242.15	284.60	452.60	404.20

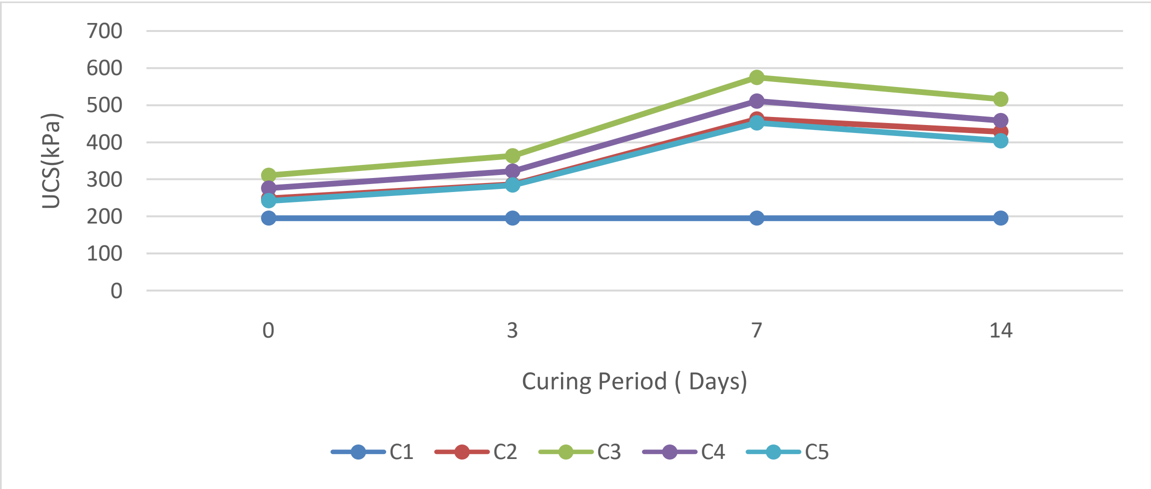

Figure 8: Variations of UCS of (Soil- CP) Mixes with curing (days)

The above fig 8 depicts that the UCS values increased significantly with the addition of CP up to 5%. The maximum UCS value of 574.70 kPa was obtained at 5% CP after 7 days of curing, which is nearly three times higher than that of plain soil. The improvement in strength may be attributed to enhanced particle interlocking and better bonding due to the fibrous structure of coffee powder. Beyond 5% CP, the UCS values decreased because excess organic content reduced compaction efficiency and increased void spaces.

Table 7: UCS Values of (Soil–FA) Mixtures

MIX	0 Days	3 Days	7 Days	14 Days
F1	195.55	195.55	195.55	195.55
F2	320.04	422.80	638.63	574.72
F3	268.40	356.20	525.80	472.60
F4	232.60	308.40	458.10	407.50
F5	198.40	262.80	408.60	350.40

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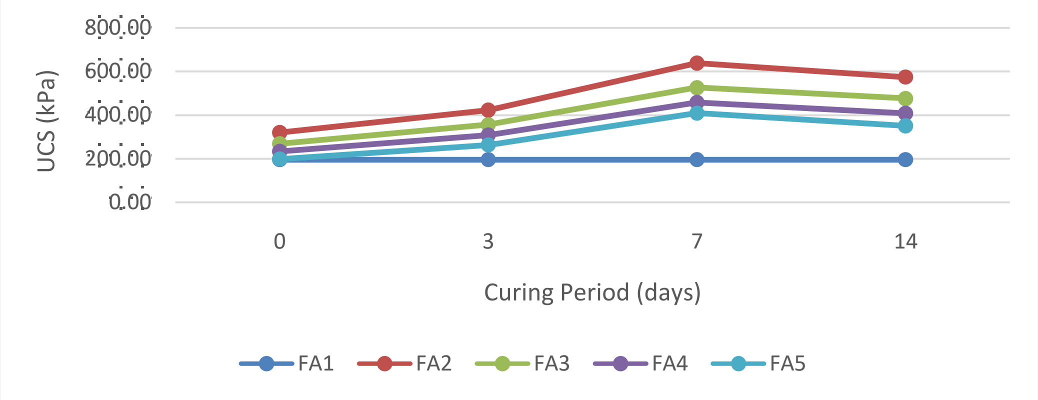

Figure 9: Variations of UCS of (Soil- FA) Mixes with curing (days)

The above fig depicts that addition of FA considerably improved UCS values due to pozzolanic reactions between Silica, Alumina, and Calcium compounds in CP and soil minerals. The highest UCS value of 638.63 kPa was observed at 5% FA after 7 days of curing. Strength gain with the curing period confirms the formation of cementitious compounds within the stabilised soil matrix.

The combined mix containing 5% CP and 5% FA showed the highest UCS value of 760.88 kPa at 7 days of curing, indicating superior performance compared to individual stabilisers.

Table 8: UCS Values of Soil and (Soil – Admixture) mixes

Mix	0 Days	3 Days	7 Days	14 Days
Untreated Soil	195.55	195.55	195.55	195.55
Soil + 5% CP	310.88	363.25	574.70	516.12
Soil + 5% FA	320.04	422.80	638.63	574.72
Soil + 5% CP + 5% FA	372.49	456.20	760.88	667.95

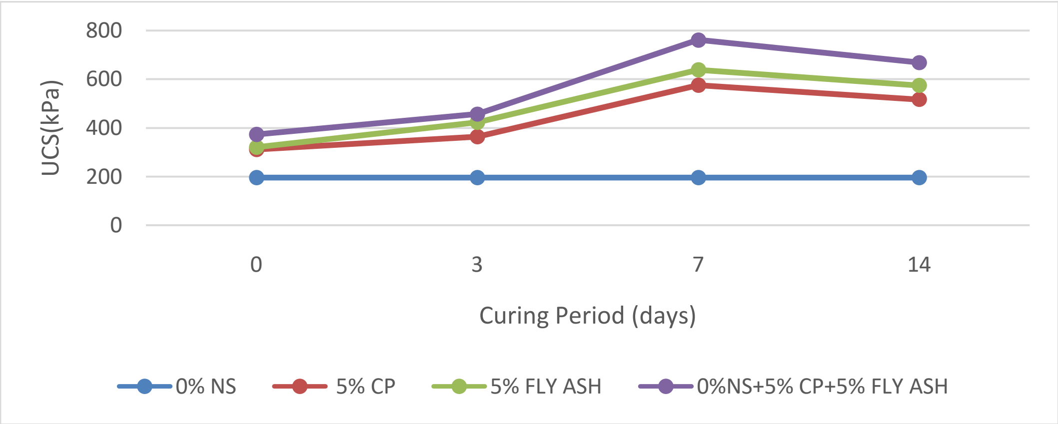

Figure 10: Variations of UCS of Soil and (Soil - Admixture) Mixes with curing

The improvement in UCS values is mainly due to the combined effects of particle bonding, pore filling, and pozzolanic reactions. The strength increased up to 7 days curing and slightly decreased at 14 days, possibly due to moisture redistribution within the specimens.

4.3 California Bearing Ratio (CBR)

California Bearing Ratio (CBR) tests were conducted on Soil and stabilised soil samples to evaluate the improvement in load-bearing capacity of expansive soil due to the addition of CP and FA. Both soaked and unsoaked CBR tests were performed for curing periods of 0, 3, 7, and 14 days. The results obtained from the tests are presented in Tables 9 and 10.

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Table 9: Unsoaked CBR Values of Soil and (Soil – Admixture) mixes with Curing days

Curing Period (Days)	Untreated Soil	Soil + 5%CP	Soil + 5%FA	Soil +5%CP +5%FA
0	12.77	20.07	13.42	16.84
3	12.77	21.48	14.68	17.62
7	12.77	22.84	16.25	20.25

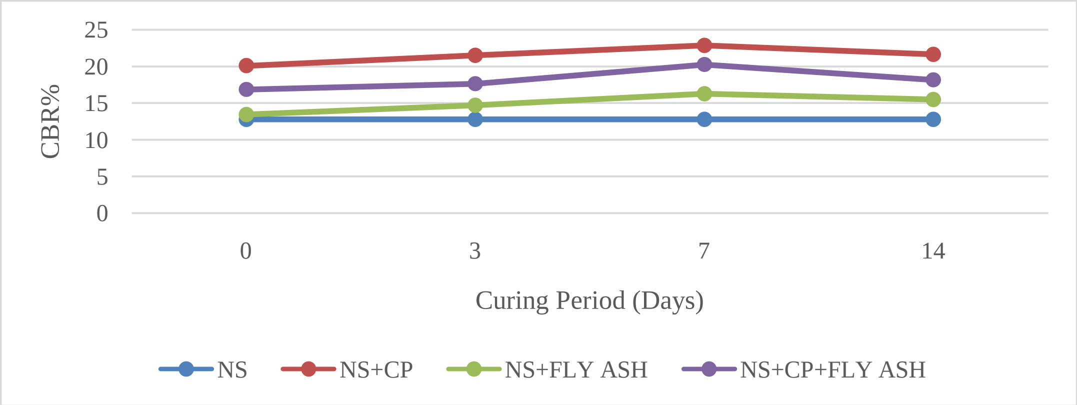

Figure 11: Variation of Unsoaked CBR with Curing Period

The unsoaked CBR results indicate that stabilisation significantly improved the bearing capacity of expansive soil. The stabilised soil mixtures exhibited considerable improvement. Soil treated with CPexibited the highest unsoaked CBR value of 22.84% at 7 days of curing, indicating enhanced particle interlocking and reduction in soil compressibility. Similarly, soil stabilised with FA exhibited improvement due to the formation of cementitious compounds resulting from pozzolanic reactions. The combined mix containing coffee powder and FA also showed a substantial increase in CBR value compared to untreated soil.

Table 10: Soaked CBR Values of Soil and (Soil – Admixture) mixes with Curing days

Curing Period (Days)	Untreated Soil	Soil + 5%CP	Soil + 5%FA	Soil + 5%CP + 5%FA
0	9.12	16.42	10.24	12.84
3	9.12	17.56	11.38	13.92
7	9.12	18.91	12.84	18.25

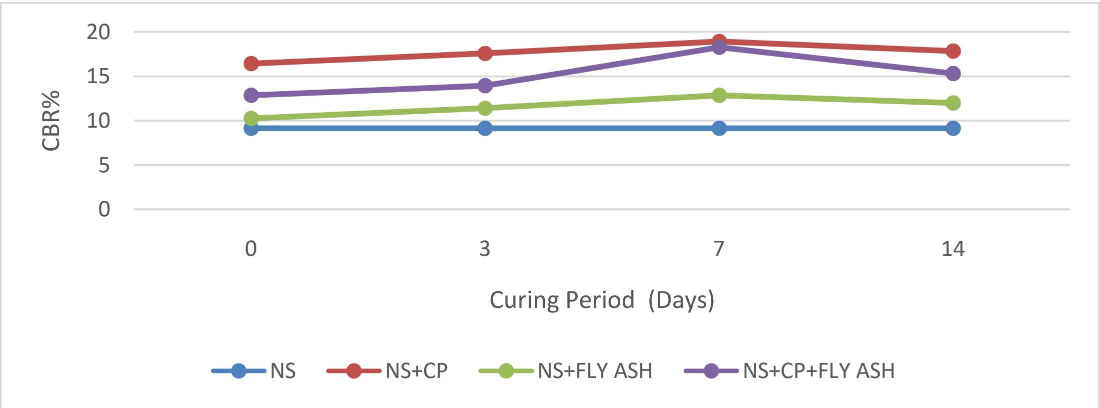

Figure 12: Variation of Soaked CBR with Curing Period

The soaked CBR values also increased considerably after stabilisation. The maximum soaked CBR value of 18.91% was obtained for soil treated with CPafter 7 days of curing. The increase in soaked CBR indicates improved resistance against moisture-induced weakening and enhanced stability under saturated conditions. The combined use of CP and FA also improved soaked CBR performance due to increased bonding and reduction in swelling potential.

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The results clearly demonstrate that stabilisation using CP and FA considerably improves the bearing capacity of expansive soil, making it suitable for pavement subgrade and foundation applications. The maximum CBR values obtained at 7 days curing indicate that adequate curing enhances the stabilisation process and development of bonding within the soil matrix.

V. SUSTAINABILITY AND PRACTICAL IMPLICATIONS

The utilization of coffee powder and fly ash for expansive soil stabilization offers significant environmental, economic, and engineering benefits. Coffee powder is an organic waste generated in large quantities from households, hotels, restaurants, and coffee industries, while fly ash is an industrial by-product produced from thermal power plants. Disposal of these materials in landfills creates environmental pollution and requires large disposal areas. The reuse of such waste materials in geotechnical applications promotes sustainable waste management and reduces environmental burden [9].

The present study demonstrates that both coffee powder and fly ash can effectively improve the engineering properties of expansive soil by increasing strength and bearing capacity while reducing swelling behavior. The use of these waste materials can reduce dependence on conventional stabilizers such as cement and lime, thereby minimizing carbon emissions and construction costs associated with traditional stabilization techniques.

The improved UCS and CBR values obtained from stabilized soil indicate that the treated soil can be effectively utilized in pavement subgrades, embankments, rural roads, and foundation applications. The use of locally available waste materials also reduces transportation costs and enhances the economic feasibility of stabilization projects in developing regions.

Furthermore, the combined stabilization approach supports sustainable construction practices by converting waste into useful engineering materials. The adoption of coffee powder and fly ash stabilization can therefore contribute toward environmentally friendly and cost-effective ground improvement techniques for future geotechnical infrastructure projects.

VI. CONCLUSIONS

Based on the experimental investigations carried out on expansive soil stabilized with Coffee Powder (CP) and Fly Ash (FA), the following conclusions are drawn:

1. The expansive soil used in the study exhibited high Plasticity; high Free Swell Index, and, making it problematic for construction applications without stabilization.
2. The addition of Coffee Powder (CP) improved the compaction characteristics of soil up to an optimum content of 5%, resulting in an increase in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC).
3. The addition of Fly Ash (FA) improved the compaction characteristics of soil up to an optimum content of 5%, resulting in an increase in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC).
4. Fly Ash (FA) stabilization improved compaction characteristics due to pozzolanic reactions and formation of cementitious compounds.
5. The maximum UCS value of 574.70 kPa was obtained for soil treated with 5% Coffee Powder, with at 7 days while Fly Ash-treated soil exhibited a maximum UCS value of 638.63 kPa at 7 days curing with 5% FA.
6. The combined mix of 5% Coffee Powder and 5% Fly Ash produced the highest UCS value of 760.88 kPa, indicating superior stabilization performance compared to individual additives.
7. Both soaked and unsoaked CBR values increased significantly after stabilization, indicating improved load-bearing capacity suitable for pavement subgrade applications.
8. The study demonstrates that Coffee Powder and Fly Ash can be effectively utilized as sustainable, economical, and eco-friendly stabilizing materials for expansive soil improvement.

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