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Effect of Fly Ash on Strength and Swelling Aspect of an Expansive Soil

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Abstract -Expansive soils pose serious challenges to lightly loaded structures due to swelling, shrinkage, and uneven settlement caused by moisture variation. This study investigates the stabilization of such soils using fly ash. Laboratory tests were conducted to compare the index, compaction, and strength properties of natural and fly ash–stabilized soils. Parameters like liquid limit, plastic limit, shrinkage limit, grain size distribution, swelling potential, maximum dry density, and optimum moisture content were evaluated. Unconfined Compression and California Bearing Ratio tests were also performed. The results indicate that adding an optimum percentage of fly ash effectively reduces swelling potential and improves strength, demonstrating its suitability for expansive soil stabilization.

Key Words: Expansive soil, Fly ash, Soil stabilization, swelling potential, Compaction characteristics, Unconfined compressive strength, California Bearing Ratio (CBR), Atterberg limits.

1. INTRODUCTION

Concrete is one of the most widely used construction materials Expansive soils have long posed challenges to engineers due to their unpredictable behavior under varying moisture conditions. These soils, which shrink upon drying and swell when wet, cause severe damage to lightly loaded structures through differential settlements and volumetric changes. The resulting deformations can lead to cracking, foundation failure, and structural instability, often rendering buildings unsafe or uninhabitable. Despite advances in geotechnical engineering, controlling the swelling potential of such soils remains a major concern in infrastructure development. Effective stabilization techniques are therefore essential to enhance their engineering performance and ensure long-term durability of structures founded on them.

Among the various stabilization approaches, the use of industrial by-products as soil additives has gained significant attention in recent years. Fly ash, a fine residue generated during coal combustion in thermal ower plants, is one such material with promising potential. Traditionally considered a waste product, fly ash poses environmental and disposal challenges due to its large-scale generation and the extensive land area required for ash ponds. Globally, countries such as China, India, the United States, and Poland together produce more than 270 million tons of fly ash annually, with India alone contributing nearly 100 million tons per year—a quantity expected to double in the coming decade.

In India, about 73 % of electricity generation is coal-based, and the majority of power plants employ wet disposal methods for fly ash. This not only consumes vast land resources but also creates environmental pollution. Hence, reusing fly ash as a stabilizing agent offers a sustainable alternative for waste utilization while improving the geotechnical properties of problematic soils. The present study investigates the influence of fly ash addition on the swelling characteristics and bearing capacity of expansive soils, aiming to develop an eco-friendly and cost-effective stabilization technique suitable for civil engineering applications.

2. AIM AND OBJECTIVES

To evaluate the effect of fly ash addition on the index, compaction, strength, and bearing characteristics of an expansive soil and identify an optimum replacement that minimizes swelling while improving engineering performance.

Objectives

1. Quantify changes in grain size distribution and specific gravity with fly ash addition.
2. Assess reductions in LL, PI, and increases in shrinkage limit indicative of lower expansiveness.
3. Determine OMC–MDD trends and identify the mix with maximum densification.
4. Measure UCS across fly ash contents to establish strength enhancement.
5. Compare unsoaked/soaked CBR to judge bearing capacity and serviceability, and infer the optimum fly ash percentage (≈20%).

3. Identification and Classification of Swelling Soils

Expansive soils are identified through laboratory and field investigations to assess their swelling potential and behaviour. Laboratory methods include microscopic examination, X-ray diffraction, and differential thermal analysis to detect clay minerals such as *montmorillonite*, which indicate high expansiveness. However, simpler techniques like the Free Swell Index (FSI) test, performed as per IS: 2720 (Part II), are widely used. In this test, 10 g of dry soil passing through a 425 µm sieve is placed in two 100 ml graduated cylinders—one containing water and the other kerosene—and the percentage increase in volume after 24 hours represents the FSI. High-grade bentonite shows FSI values between 1200–2000%, whereas soils with FSI below 50% exhibit minimal swelling.

The swelling potential of soil can also be correlated with Atterberg limits, particularly the plasticity index (PI). Soils with PI values of 0–15% show low, 10–35% medium, 35–55% high, and above 55% very high swelling potential. Additional parameters like liquid limit, shrinkage limit, and grain size distribution further assist in classification. The IS: 1498 system categorizes soils based on liquid limit, plastic limit, shrinkage limit, and FSI, defining degrees of expansion from low to very high.

Swelling behaviour depends on the difference between field moisture content and the equilibrium moisture content after construction. When expansive soils absorb moisture, they exert swell pressure, leading to heaving or distress in structures. Factors influencing swelling include initial moisture content, density, stress history, temperature, pore fluid, and overburden pressure. High clay content near the surface typically results in greater swelling.

To mitigate these issues, various stabilization and control measures are used, such as moisture barriers, pre-wetting, compaction control, soil replacement, and Cohesive Non-Swelling (CNS) layers. These methods reduce volume change, swelling pressure, and differential settlement, ensuring better structural stability in expansive soil regions.

4. Experimental Procedures

4.1 Grain Size Analysis

Grain size distribution was determined for both expansive soil and fly ash using two methods: mechanical sieve analysis and hydrometer analysis. The procedures were carried out as per the specifications of IS: 3104–1964, enabling the classification of soil based on particle size distribution.

4.2 Specific Gravity

The specific gravity of the expansive soil was determined using a pycnometer (volumetric flask) in accordance with IS: 2720 (Part III / Section 1) – 1980. This test helps to assess the density relationship between soil solids and water, which is essential for further soil property evaluations.

4.3 Liquid Limit

The liquid limit was determined using the standard Casagrande apparatus as specified in IS: 9259–1979. Approximately 120 g of soil passing through a 425 µm sieve was used. The number of blows required to close the groove made by the standard tool was recorded, and the water content corresponding to 25 blows was taken as the liquid limit. Tests were conducted for both untreated expansive soil and soil blended with 20% fly ash.

4.4 Plastic Limit

The plastic limit was determined in accordance with IS: 2720 (Part V) – 1986 for expansive soil and soil stabilized with 20% fly ash. This test identifies the water content at which the soil changes from a plastic to a semi-solid state.

4.5 Optimum Moisture Content and Maximum Dry Density

The Standard Proctor Test, as per IS: 2720 (Part VII) – 1965, was performed to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the expansive soil mixed with varying percentages of fly ash (0%, 10%, 20%, 30%, 40%, and 50%). Each sample was compacted in a standard mould in three layers, with each layer receiving 25 blows from a 2.6 kg rammer dropped from a height of 31 cm. The resulting dry density values were plotted against corresponding water contents to determine OMC and MDD.

4.6 Free Swell Index

The Free Swell Index (FSI) of untreated and fly ash–stabilized soil (0–50%) was determined following IS: 2720 (Part II). Two oven-dried soil samples (20 g each, passing through a 425 µm sieve) were placed in 100 ml graduated cylinders—one filled with distilled water and the other with kerosene. After 24 hours, the final volumes were recorded to calculate the free swell index, which indicates the degree of expansiveness.

4.7 Unconfined Compression Test

The Unconfined Compressive Strength (UCS) of soil samples mixed with different fly ash percentages (0%, 10%, 20%, 30%, 40%, and 50%) was determined at their respective OMCs, as per IS: 2720 (Part X) – 1991 and IS: 4330 (Part V) – 1970. This test evaluates the strength and stress–strain characteristics of stabilized soil under axial loading.

4.8 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) test was performed on soil–fly ash mixtures with varying fly ash contents (0%, 10%, 20%, 30%, 40%, and 50%) according to IS: 2720 (Part XVI) – 1961. Specimens were compacted at their OMC and tested under both unsoaked and soaked conditions (after 4 days of immersion). The CBR values were used to assess the improvement in subgrade strength due to fly ash stabilization.

5. Result and discussion

Grain size distribution.The swelling soil shows a high fines fraction: cumulative percent finer reaches ~69% by 0.075 mm (sieve) and hydrometer data indicates substantial clay–silt (<0.02 mm), confirming its expansive character. Fly ash is overwhelmingly fine (≈34% ≤0.075 mm; ≈56% between 0.150–0.075 mm), so its addition enriches the matrix with micro-fines that fill voids and alter compaction/water-demand behavior.

Specific gravity.Soil Gs ≈ 2.30–2.41; fly ash Gs ≈ 2.24–2.25. The slightly lower Gs of fly ash reduces mix unit weight and typically shifts OMC upward, consistent with compaction results.

Atterberg & shrinkage limits.For natural soil, LL (from flow curve near 25 blows) is high (~66–68%), PL ≈ 37.5% → PI ≈ 29–31%, confirming high plasticity/expansiveness. With 20% fly ash, LL drops to ~56–58% and PL ≈ 34.7%, giving PI ≈ 21–23%—a clear reduction in plasticity. Shrinkage limit increases from 15.75% (soil) to 18.87% (soil+20% FA), indicating lower susceptibility to volume change at low moisture contents.

Free swell index (FSI).FSI falls from 47.6% (soil) to a minimum 31.6% at 20% fly ash, then rises again at ≥30% FA (≈37–47%). Thus, ~20% FA is optimal for mitigating swell in this dataset.

Compaction (Standard Proctor).Natural soil reaches max dry density (MDD) ≈ 1.49 g/cc at OMC ≈ 21%. With 10% FA, MDD ~1.47 g/cc at higher OMC (~27%). The best response occurs at 20% FA with MDD ≈ 1.526 g/cc at OMC ≈ 22%, suggesting improved packing (fines filling and pozzolanic flocculation). Beyond 20% FA, MDD declines (≈1.43–1.40 g/cc) and OMC trends higher—typical when excess fines increase water demand without proportional densification.

Unconfined compressive strength (UCS).Peak UCS for natural soil is ~0.146 MPa; 10% FA ~0.111 MPa; 20% FA peaks near 0.152 MPa (highest among mixes), evidencing early pozzolanic/particle-reinforcement benefits. At 30–50% FA, UCS declines (~0.10–0.12 MPa), aligning with the compaction trend.

California Bearing Ratio (CBR). Unsoaked CBR improves substantially: soil 6.24% (2.5 mm)/5.55% (5 mm) → 10% FA: 11.73/10.60 → 20% FA: 23.27/20.44 (optimum). At ≥30% FA, gains recede (~8–10%). Under soaked conditions, values remain low across mixes (soil 3.40/2.77; 10–50% FA ≈1.5–2.8), indicating that fly ash alone (without lime/cement and proper curing) does not sufficiently improve saturated bearing; drainage and/or stabilizer blends are advised for wet service.

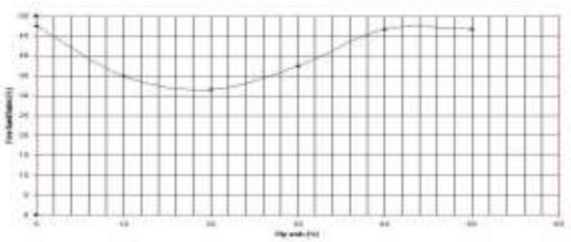

Fig-1: Free swell index at various percentages of fly-ash

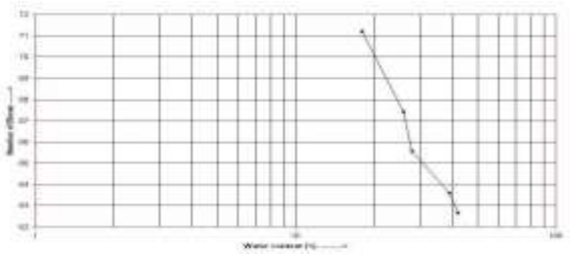

Fig-2: Liquid limit of swelling soil

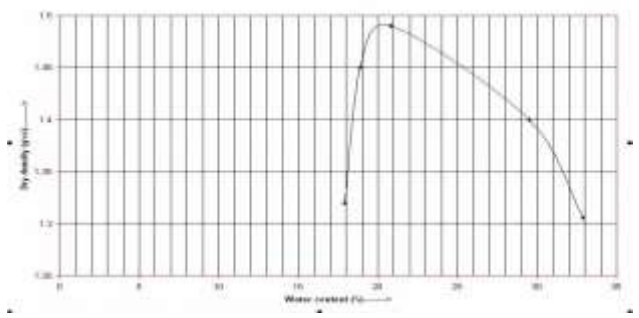

Fig-3: Proctor compaction Test for swelling soil

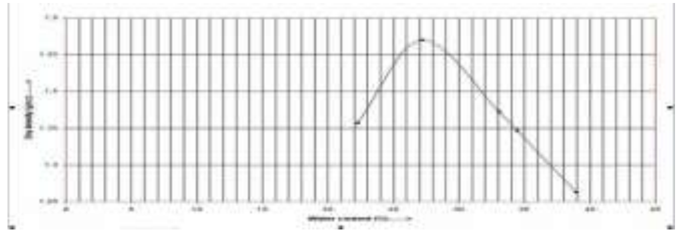

Fig-4: Proctor compaction Test with swelling soil+10%fly-ash

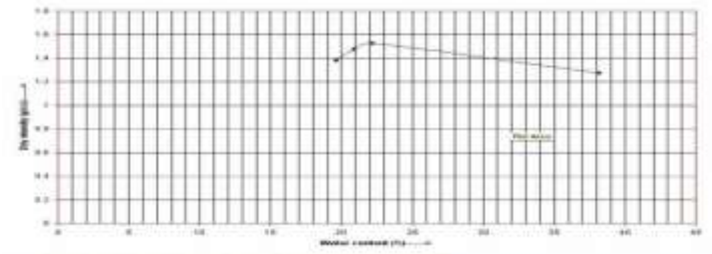

Fig-5: Proctor compaction Test with swelling soil+20% fly-ash

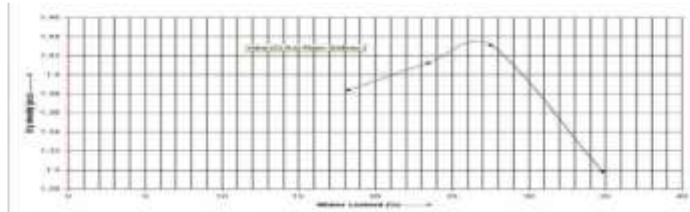

Fig-6: Proctor compaction Test with swelling soil+30% fly-ash

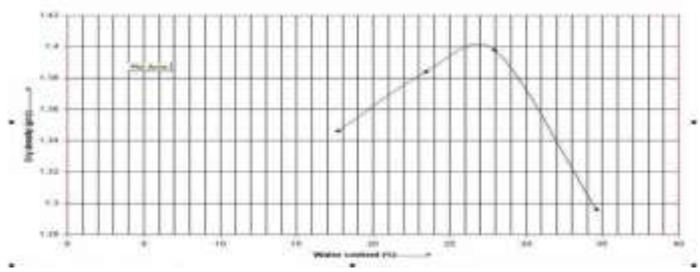

Fig-7: Proctor compaction Test with swelling soil+40% fly-ash

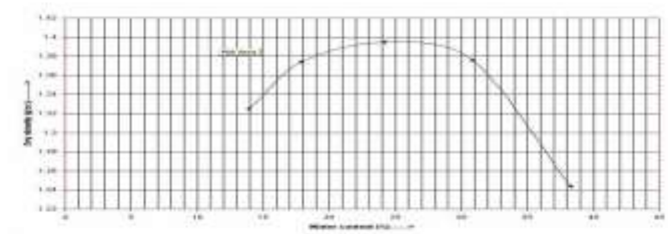

Fig-8: Proctor compaction Test with swelling soil+50% fly-ash

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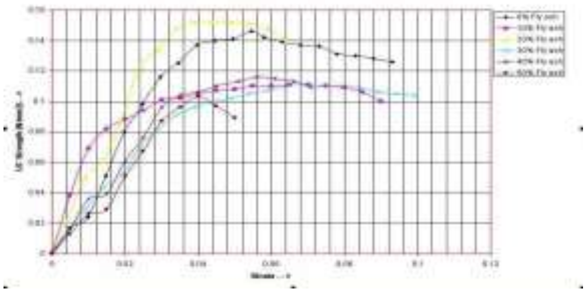

Fig. 9: Comparison between different percentages of fly-ash results obtained from the "UCS" test

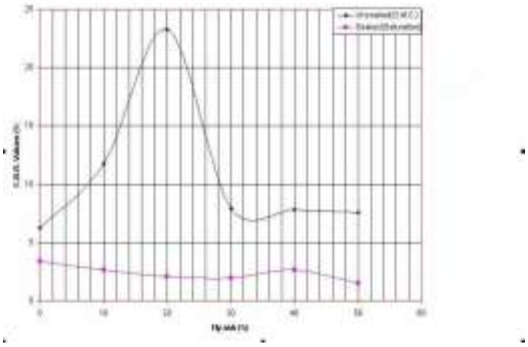

Fig. 10: California bearing ratio values of swelling soil with various percentages of fly-ash

6. CONCLUSIONS

The experimental investigation clearly demonstrates that the addition of fly ash significantly improves the engineering behaviour of expansive soil. The free swell index decreases steadily with increasing fly ash content, reaching its minimum value at 20%, indicating an effective reduction in swelling potential. The unconfined compressive strength initially decreases up to 10% fly ash but attains a maximum value at 20%, reflecting enhanced bonding and strength development due to pozzolanic activity. A further increase in fly ash content beyond this level results in a gradual decline in strength.

Similarly, the California Bearing Ratio (CBR) value of the unsoaked sample tested at Optimum Moisture Content (OMC) attains its highest value of 23.27% at 20% fly ash, confirming this proportion as the optimum mix for subgrade improvement. The Proctor compaction test results also indicate maximum dry density (1.54 g/cc) and minimum OMC (22.29%) at 20% fly ash, emphasizing better packing and reduced void ratio. Moreover, the Atterberg limits exhibit notable improvement, showing minimum plasticity and increased stability at the same dosage.

Hence, it can be concluded that 20% fly ash content provides the optimum stabilization for expansive soils, effectively reducing swell potential while improving strength, density, and load-bearing capacity. The use of fly ash not only enhances the geotechnical properties of problematic soils but also promotes sustainable waste utilization, offering an eco-friendly and economical solution for ground improvement in civil engineering applications.

7. Scope further studies

Further study can focus on:

- Evaluating long-term durability of fly ash–ash-stabilized soils under field conditions.
- Investigating combined use of fly ash with lime, cement, or GGBS for enhanced stabilization.
- Conducting microstructural analysis (SEM/XRD) to understand pozzolanic reactions.
- Performing field trials to validate laboratory results and assess real-time behavior.
- Carrying out environmental and economic assessments for large-scale applications.
- Studying performance under dynamic or traffic loads for pavement and foundation design.

These studies will support wider and more sustainable use of fly ash in soil stabilization.

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