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A Study on the Performance of Expansive Soil Treated with Copper Slag and Geopolymer for Pavement Subgrade

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Abstract: Expansive soils, known for their high plasticity and pronounced shrink–swell behavior, pose a major threat to the stability and performance of pavement subgrades in regions with seasonal moisture fluctuations. Conventional stabilizers such as lime and cement, while effective, contribute significantly to carbon emissions and energy consumption. In response, this study explores a sustainable and high-performance alternative by employing copper slag, an industrial by-product, in combination with geopolymer binders synthesized from sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. The research aims to evaluate the mechanical, compaction, and durability characteristics of expansive soil stabilized using varying proportions of copper slag and geopolymer for potential application in flexible pavement subgrades. A systematic laboratory investigation was conducted wherein copper slag was incorporated at 5%, 10%, 15%, and 20%, and the geopolymer activator was varied between 0.5% and 2.0% by weight of soil. Standard geotechnical tests, including Atterberg limits, compaction, Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR), were performed in accordance with IS: 2720 specifications. The inclusion of copper slag led to a marked reduction in plasticity and an increase in maximum dry density (from 1.51 g/cc to 1.75 g/cc), while the geopolymer binder contributed to chemical bonding and improved soil matrix integrity. The optimum combination of 15% copper slag and 1.5% geopolymer exhibited significant improvements, with the CBR value increasing from 1.59% to 8.72% and the UCS value showed almost a twofold improvement over untreated soil. The results indicate that the synergistic interaction between copper slag and geopolymer enhances both the mechanical interlocking and chemical cementation within the soil structure, leading to superior strength, stiffness, and moisture resistance. The stabilized soil satisfies the minimum CBR requirement (≥8%) for subgrade material as per IRC:37–2018, confirming its suitability for use in flexible pavement foundations. This study thus establishes a sustainable, low-carbon, and durable alternative for expansive soil stabilization, promoting the beneficial reuse of industrial waste and supporting the principles of green geotechnical engineering and circular economy.

Keywords: Expansive Soil (ES), Copper Slag (CS), Alkali-Activated Geopolymer (AAG), Soil Stabilization, Pavement Subgrade, Flexible Pavement, Sustainable Construction, Industrial Waste Utilization.

I. INTRODUCTION

Expansive soils, which are predominantly found in semi-arid and tropical regions of India, present one of the most challenging geomaterials for civil and transportation infrastructure development. These soils, primarily composed of montmorillonite and other clay minerals, exhibit a pronounced tendency to undergo swelling upon wetting and shrinkage upon drying, resulting in severe volume changes. Such cyclic volumetric instability causes heaving, cracking, and differential settlement in structures founded on or constructed over these soils, particularly flexible pavements, embankments, and light foundations. The behavior of expansive soils is largely governed by their mineralogical composition, high plasticity, and low shear strength. In their natural state, these soils possess low bearing capacity, high compressibility, and poor drainage, rendering them unsuitable as subgrade materials without modification. With rapid infrastructure expansion in India—especially road and highway projects—the stabilization of expansive soils has become a crucial component of sustainable pavement engineering. Traditionally, stabilizing agents such as lime, cement, and fly ash have been employed to improve the engineering properties of expansive soils. Although these additives enhance strength and reduce plasticity, their large-scale use raises environmental concerns due to high carbon emissions, energy-intensive production, and depletion of natural resources. Consequently, there is a growing demand for eco-friendly, cost-effective, and durable alternatives that not only improve soil performance but also promote industrial waste utilization.

In this context, copper slag, an industrial by-product obtained from the smelting and refining of copper, offers significant potential as a soil stabilizer. It is a non-plastic, granular material rich in silica and iron oxide, possessing good pozzolanic characteristics and angular particle geometry that improves the soil's density and interparticle friction. Additionally, the increasing availability of copper slag from industries in India provides an opportunity for its beneficial reuse in geotechnical applications, reducing disposal problems and environmental pollution.

Complementing this, geopolymers—inorganic binders synthesized through the alkaline activation of alumino-silicate materials such as fly ash or slag—have emerged as sustainable substitutes for conventional cementitious binders. The chemical reaction between sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) produces a polymeric Si–O–Al framework, which contributes to higher early strength, durability, and environmental compatibility. When used in soil stabilization, geopolymers enhance cohesion, stiffness, and load-bearing capacity by forming a cementitious matrix that binds soil particles together.

The combined application of copper slag and geopolymer presents a synergistic approach: copper slag provides particle densification and pozzolanic reactivity, while geopolymer contributes to strong bonding and long-term durability. Such combinations can lead to substantial improvements in California Bearing Ratio (CBR) and compaction characteristics, thereby fulfilling the performance requirements for subgrade materials as per IRC:37–2018.

This study focuses on evaluating the performance of expansive soil stabilized with varying proportions of copper slag and geopolymer. The investigation aims to determine the optimum mix proportion that yields maximum strength and durability, while promoting the sustainable utilization of industrial by-products in pavement subgrade construction. The outcomes of this research contribute to the advancement of eco-efficient soil stabilization techniques, aligning with India's commitment to sustainable and resilient infrastructure development.

Figure 1: Pavement uplift and longitudinal crack caused by expansive soil

II. MATERIALS AND METHODS

A. *Expansive Soil*

The soil used in this investigation is expansive clay, collected from a depth of approximately 1.5 meters below the ground surface at the soil sample collection site in Yanamadala, Ramachandrapuram, Andhra Pradesh, India (Lat. 16.84672°, Long. 82.07725°). The collected soil was air-dried, pulverized, and sieved through a 4.75 mm IS sieve before being used for testing.

Preliminary identification and classification tests were conducted in accordance with IS: 2720 (Part 1–5) to determine the physical and index properties of the soil. The test results revealed that the soil exhibits high plasticity, low strength, and significant swelling potential, which are characteristic features of expansive soils. Based on the Atterberg limits and grain size distribution, the soil was classified as CH – Highly Plastic Clay according to the Unified Soil Classification System (USCS).

The presence of montmorillonite clay mineral contributes to its high shrink–swell behavior and poor performance as a pavement subgrade. Hence, stabilization was undertaken using copper slag and geopolymer binder to improve its engineering properties.

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B. Copper Slag

Copper slag (CS) is a by-product generated during the matte smelting and refining of copper ore. It is a coarse, angular, glassy material with a dark black appearance and a specific gravity ranging from 3.3 to 3.6. The material primarily consists of silica (SiO_2), iron oxide (Fe_2O_3), alumina (Al_2O_3), and calcium oxide (CaO). The slag used in this study was collected from Sterlite Copper Industry, Thoothukudi, Tamil Nadu, India, where large volumes of slag are produced annually.

Copper slag was oven-dried at 105°C, pulverized, and sieved through a 425 µm sieve to achieve uniform grading suitable for mixing with soil. Its pozzolanic nature and angular particle shape enhance soil densification and interparticle bonding when combined with an activator or binder.

In the present study, copper slag was added in varying percentages of 5%, 10%, 15%, and 20% by dry weight of soil, and the corresponding improvements in soil properties were investigated

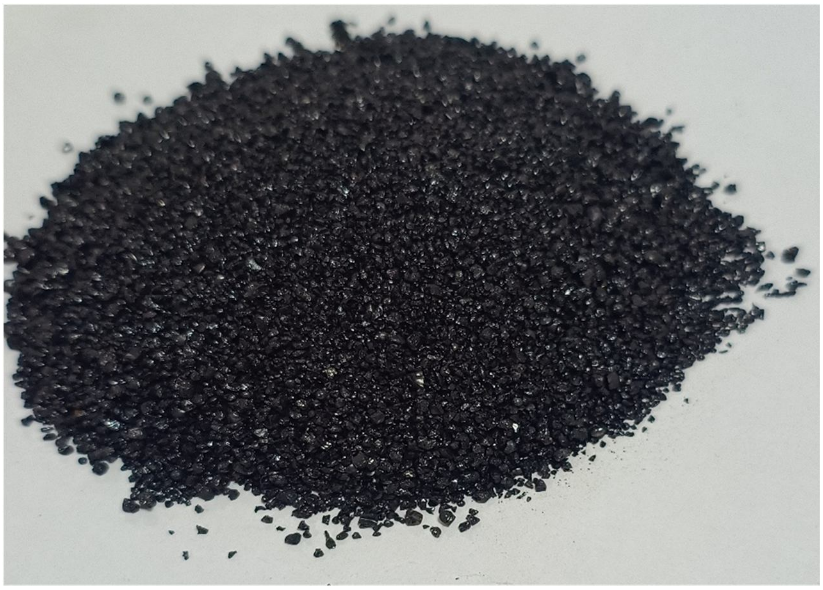
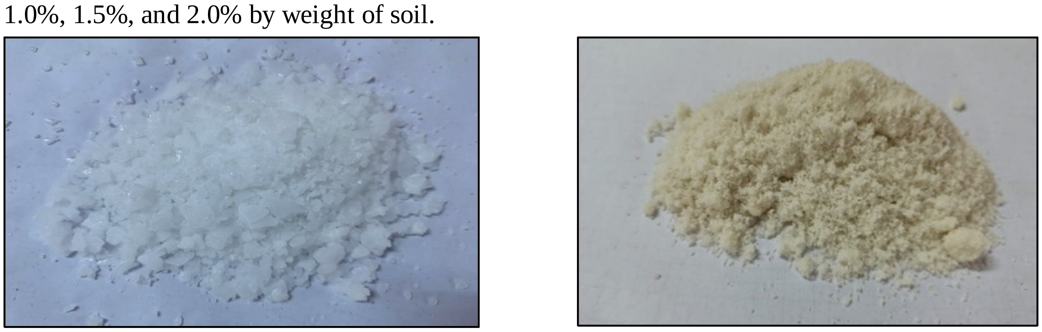


Figure 2: Copper Slag Sample

C. Alkaline Activators Geopolymers (AAG)

The geopolymer binder was synthesized by activating an alumino-silicate source material (fly ash) with an alkaline solution prepared from sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The NaOH pellets of 98% purity were dissolved in distilled water to form a 10M solution, which was then mixed with sodium silicate in a ratio of 2.5:1 (Na_2SiO_3: NaOH) by weight. The prepared activator solution was allowed to equilibrate for 24 hours prior to use to ensure complete chemical reactivity.

The geopolymer solution acts as a binder that reacts with silica and alumina present in the soil and copper slag to form a polymeric Si–O–Al network, enhancing the soil's cohesion, compressive strength, and water resistance. The geopolymer dosages used in this study were 0.5%, 1.0%, 1.5%, and 2.0% by weight of soil.



Sodium hydroxide **Sodium silicate (Na_2SiO_3)**

Figure 3: Sodium hydroxide (NaOH) & Sodium silicate (Na_2SiO_3)

D. Objective of Study

The objectives of the present experimental study are

1) To perform comprehensive index and engineering property tests including particle size analysis, Atterberg limits, compaction, and CBR to establish the baseline behavior of untreated expansive soil.
2) To analyze how copper slag contributes to reducing plasticity and swelling while promoting better compaction and load-bearing characteristics.
3) To compare the performance of treated and untreated soils and identify the optimum mix proportion for best improvement.
4) To conduct California Bearing Ratio (CBR) and Cyclic Plate Load Tests on both untreated and treated Expansive Soil samples to quantitatively evaluate the improvement in stiffness, resilience, and deformation characteristics.
5) To contribute toward the development of eco-friendly, low-carbon soil stabilization methods, aligning with global sustainability goals in infrastructure development.

This study investigates the potential of Copper Slag (CS) combined with Alkaline Activator-Based Geopolymer (AAG) as a sustainable soil stabilizer for expansive soil (ES) and evaluates its effectiveness as a pavement subgrade material.

III. LITERATURE REVIEW

1) (S. G. Patel and R. Kumar, 2024) This study investigated the stabilization of expansive clay using copper slag and lime as hybrid stabilizers. The results demonstrated that the addition of 15% copper slag significantly increased the maximum dry density (MDD) and reduced the optimum moisture content (OMC) due to the dense packing of slag particles. The California Bearing Ratio (CBR) improved from 2.5% (untreated) to 8.6% (treated), confirming that copper slag effectively enhances the load-bearing capacity of expansive soils. The study emphasized that the angular texture and pozzolanic activity of copper slag contribute to better interparticle bonding and strength gain, making it a suitable replacement for conventional granular materials in subgrade stabilization.
2) (V. N. Harini and D. Chandrasekhar, 2023) An experimental investigation was conducted on the use of fly ash-based geopolymer binders for improving the properties of black cotton soil. The geopolymer solution was prepared using NaOH (10M) and Na_2SiO_3 with a ratio of 2.5:1. The study revealed a substantial increase in UCS and CBR values with an optimum geopolymer content of 1.5%. The strength gain was attributed to the formation of alumino-silicate gel that bound the clay particles together. Microstructural analysis through SEM and XRD indicated the development of C–S–H and N–A–S–H gels, contributing to improved soil fabric and durability. The study concluded that geopolymers are an eco-efficient substitute for cement and lime in expansive soil stabilization.
3) (M. S. Pillai and R. Ramesh, 2022) This research focused on evaluating the combined use of industrial waste copper slag and geopolymer for stabilizing high-plasticity clay soils. The results showed that the addition of 10–20% copper slag and 1–2% geopolymer binder improved the compaction density and UCS by up to 70% compared to untreated soil. The plasticity index decreased from 35% to 12%, indicating reduced swelling potential. The study also highlighted the sustainability benefits of this approach, as it reduced CO_2 emissions and effectively utilized large volumes of industrial waste materials that would otherwise be landfilled.
4) (N. Venkatesh and P. Srinivas, 2021) An extensive laboratory investigation was carried out to evaluate the performance of copper slag-treated expansive soils for road subgrades. The inclusion of 20% copper slag resulted in a 25% increase in MDD and a 40% decrease in OMC, enhancing the compactability of soil. The CBR increased from 2.3% to 9.1%, meeting the requirements of IRC:37–2018 for flexible pavements. The researchers concluded that copper slag provides both mechanical interlocking and chemical stabilization when combined with alkaline binders, making it a promising stabilizer for expansive clayey subgrades in road construction.
5) (G. Rajesh and A. R. Sudhakar, 2020) This study investigated the stabilization of expansive soil using fly ash–geopolymer blends as a replacement for cement. The research showed that the strength of the treated soil increased steadily up to 28 days of curing, with a peak UCS of 580 kPa at 1.5% geopolymer content. The plasticity index and free swell index were reduced by more than 60%, indicating a significant improvement in dimensional stability. The study concluded that geopolymerization forms a rigid matrix, binding clay particles and reducing their affinity for water, thereby minimizing swelling and shrinkage.
6) (M. Ahmed and K. Das, 2019) An experimental analysis was performed on the combined influence of copper slag and ground granulated blast furnace slag (GGBS) on expansive clay. The optimum mix (15% CS + 5% GGBS) enhanced the CBR value from 2.8% to 10.2%, while UCS increased by more than threefold. The study found that the inclusion of copper slag not only improved the physical structure of soil but also promoted pozzolanic reactions with calcium-bearing compounds in GGBS,

resulting in a dense, durable, and water-resistant subgrade layer. The findings emphasized the potential of using industrial waste synergy for sustainable ground improvement.

IV. RESULTS & DISCUSSION

Table -1: Chemical Properties of CS & AAG

S. No.	Constituent	Chemical Formula	Copper Slag (%)	Sodium Hydroxide (NaOH)	Sodium Silicate (Na_2SiO_3)
1	Silica	SiO_2	35.60	-	36.0
2	Alumina	Al_2O_3	3.80	-	-
3	Iron Oxide	Fe_2O_3	48.70	-	0.05
4	Calcium Oxide	CaO	4.20	-	-
5	Magnesium Oxide	MgO	1.10	0.10	-
6	Sodium Oxide	Na_2O	-	76.20	12.0
7	Potassium Oxide	K_2O	0.40	-	-
8	Loss on Ignition (LOI)	—	2.20	3.70	2.60
9	Water	H_2O	-	20.00	70.00

Table – 2: Properties of Untreated Expansive Soil

S. No	Properties		Symbol	Untreated Expansive Soil
1	Particle Size Distribution	Gravel (%)		0
		Sand (%)		7.76
		Silt (%)		21.6
		Clay (%)		70.64
2	Differential free swell (%)		DFS	95
3	Natural Moisture Content (%)			81.43
4	Specific gravity		G	2.35
5	Liquid Limit (%)		W_L	74.51
5	Plastic Limit (%)		W_p	32.74
6	Plasticity Index (%)		I_p	41.77
7	Soil Classification			CH
8	Maximum Dry Density (gm/cc)		M.D. D	1.51
9	Optimum Moisture Content (%)		O.M.C	29.72
10	CBR Value (soaked) (%)			1.59
11	cohesion (kN/m^{2})		C	1.48
12	Angle of internal friction		ø	2.83

A. Differential Free Swell

Table – 3: Mix Proportions used for testing

S. No	Mix Proportion	DSF
1	85%ES + 15% CS + 0% Geopolymer	52.00
2	84.5%ES + 15% CS + 0.5% Geopolymer	38.00
3	84.%ES + 15% CS + 1 Geopolymer	27.00
4	83.5%ES + 15% CS + 1.5% Geopolymer	18.00
5	83.%ES + 15% CS + 2% Geopolymer	15.00

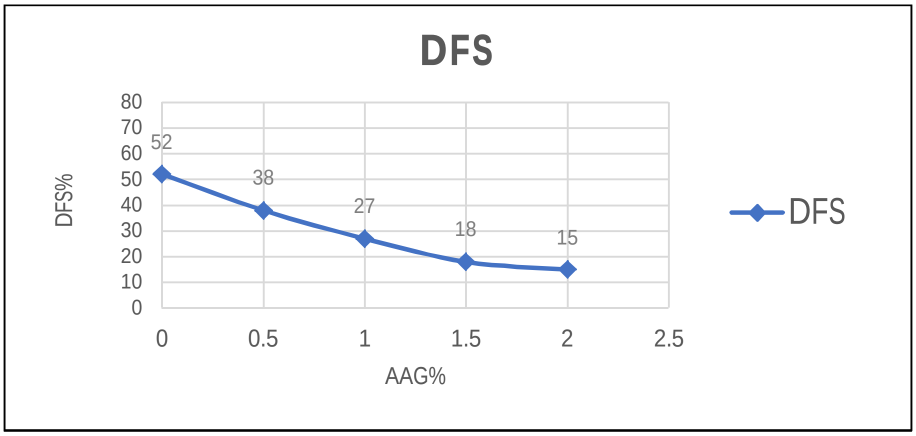


Figure 4: Variation of DFS of ES Treated with 15% of CS with Different Percentages of AAG

Figure 4 shows that the DFS values decreases from 52% to 15% on addition of optimum percentage CS and AAG addition of AAG from 0.5 to 2%.

B. Atterberg Limits

Table – 4: Show LL, PL, PI treated ES soil

S. No	Mix Proportion	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
1	100% ES	74.51	30.74	43.77
2	84.5%ES + 15% CS + 0.5 Geopolymer	63.35	34.86	28.49
3	84%ES + 15fi CS + 1 Geopolymer	55.46	38.53	16.93
4	83.5%ES + 15% CS + 1.5 Geopolymer	48.36	40.11	8.25

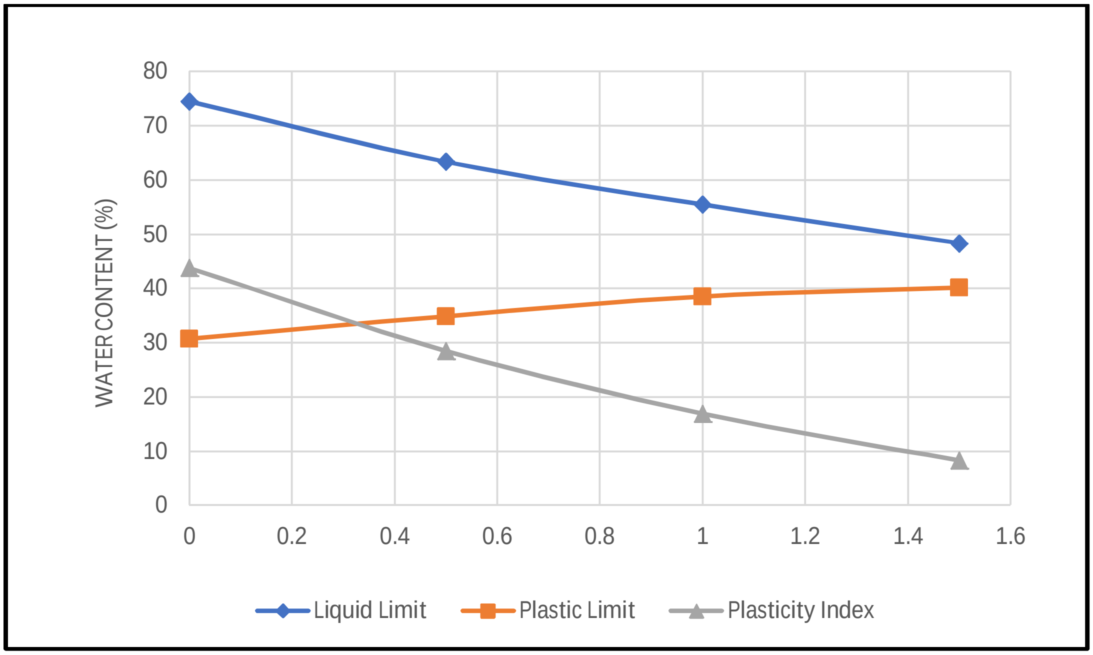


Figure 5: Variation of LL, PL and PI of ES Treated with 15% of CS with Different Percentages of AAG

Figure 5 shows that the PL, LL, and PI values decrease from 43.77% to 8.25% on addition of optimum percentage CS and AAG addition of AAG from 0.5 to 1.5%.

C. OMC & MDD

Table-5: OMC and MDD values of treated ES soil

S. No	Mix Proportion	OMC (%)	MDD (gm/cc)
1	85% ES + 15%CS + 0% Geopolymer	21.72	1.55
2	84.5%ES + 15% + 0.5% Geopolymer	17.86	1.59
3	84%ES + 15% CS + 1% Geopolymer	16.93	1.69
4	83.5%ES + 15% CS + 1.5% Geopolymer	14.77	1.75
5	83%ES + 15% CS + 2% Geopolymer	15.16	1.68

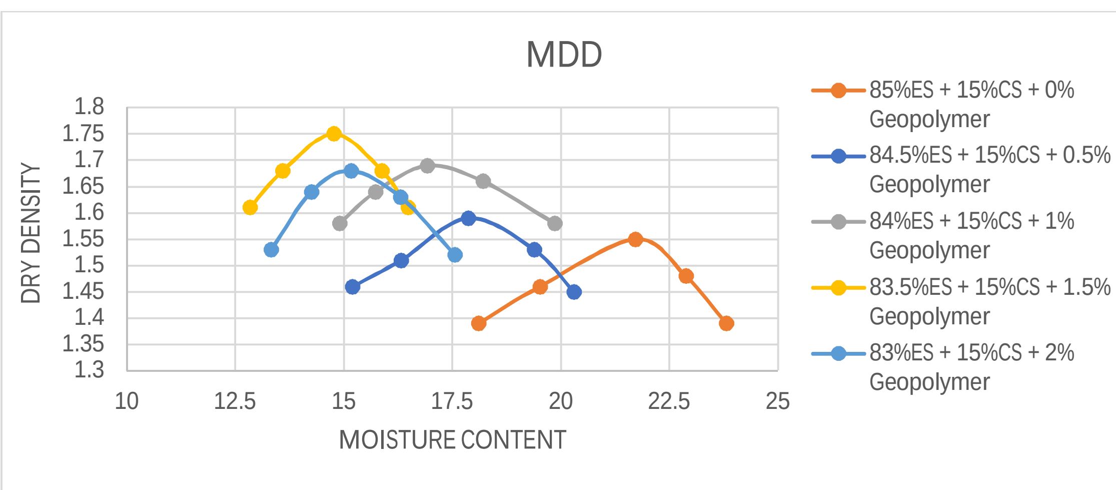


Figure 6: Variation of OMC and MDD of ES treated with 15% CS with various percentages of AAG

Table 5 shows that the OMC values decrease from 21.72% to 14.77% on addition of optimum percentage CS and AAG addition of AAG from 0.5 to 2%. The MDD values of the treated ES soil was observed to be increased from 1.55 g/cc to 1.75 g/cc on addition of optimum percentage CS and AAG addition of AAG from 0.5 to 2%. The optimum% of AAG Is 1.5.

D. California Bearing Ratio (CBR)

Table-6: CBR Test Results for different mix proportions

S. No	Mix Proportion	CBR (%)
1	85% ES + 15% CS + 0% Geopolymer	4.93
2	84.5%ES + 15% CS + 0.5 Geopolymer	6.72
3	84%ES + 15% CS + 1 Geopolymer	7.62
4	83.5%ES + 15% CS + 1.5 Geopolymer	8.78
5	83%ES + 15% CS + 2% Geopolymer	7.89

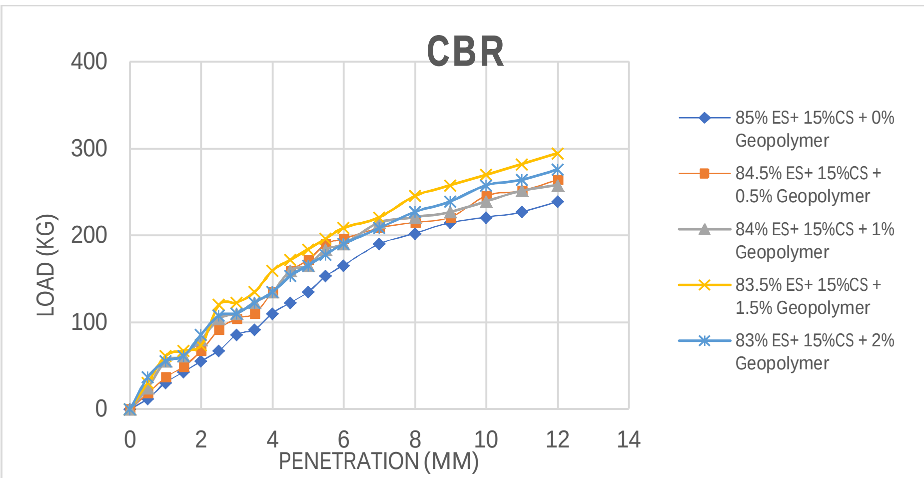


Figure 7: Variation of CBR of ES Treated with 15% CS and Various percentages of AAG

Table 7 shows that the CBR is increased from 4.93% to 8.78% after adding Optimum percentage CS and AAG addition of Optimum AAG from 1.5% mix.

Table-7: Properties of untreated and treated expansive soil

S. No	Properties	Symbol	Untreated Expansive Soil	Expansive soil + 15% Copper Slag	Expansive soil + 15% Copper Slag + 1.5% Geopolymer
1	Liquid Limit (%)	W_L	74.51	62.13	48.36
2	Plastic Limit (%)	W_p	32.74	33.25	40.11
3	Plasticity Index (%)	I_p	41.77	30.88	8.25
4	Specific gravity	G	2.35	2.57	2.61
5	Differential free swell (%)	DFS	95	52	15
6	Maximum Dry Density (gm/cc)	M.D. D	1.51	1.55	1.75
7	Optimum Moisture Content (%)	O.M.C	29.72	19.31	18.77
8	CBR Value (soaked) (%)		1.59	4.85	8.78
9	cohesion (kN/m^{2})	C	148.32	92.86	81.56
10	Angle of internal friction	ø	2.83	3.10	4.86

V. CONCLUSION

1) It is observed from the laboratory test results that the Differential Free Swell Index (DFS) of expansive soil reduced by 45.26% with the addition of 15% Copper Slag, and it has been further reduced by 71.15% with the inclusion of 1.5% Geopolymer binder compared to untreated soil.
2) It is observed from the laboratory test results that the Liquid Limit (WL) of expansive soil decreased by 13.89% with the addition of 15% Copper Slag, and it further decreased by 24.55% with the addition of 1.5% Geopolymer.
3) It is observed from the laboratory test results that the Plastic Limit (WP) increased by 1.56% on addition of 15% Copper Slag, and further increased by 20.67% with the inclusion of 1.5% Geopolymer binder.
4) It is noticed that the Plasticity Index (IP) decreased by 26.07% on addition of 15% Copper Slag, and it has been further decreased by 73.28% with the addition of 1.5% Geopolymer compared to untreated soil.
5) It is observed from the laboratory test results that the Specific Gravity (G) of the expansive soil increased by 9.36% on addition of 15% Copper Slag, and it further increased by 1.56% with the inclusion of 1.5% Geopolymer binder, indicating improved particle packing and density.
6) It is observed from the laboratory test results that the Optimum Moisture Content (OMC) decreased by 35.04% on addition of 15% Copper Slag, and it has been further decreased by 2.79% with the addition of 1.5% Geopolymer binder.
7) It is observed from the laboratory test results that the Maximum Dry Density (MDD) increased by 2.65% with the addition of 15% Copper Slag, and it further increased by 12.90% with the inclusion of 1.5% Geopolymer binder, indicating densification and improved compactability.
8) It is observed that the CBR (Soaked) value increased by 205.66% with the addition of 15% Copper Slag, and it further increased by 80.41% with the addition of 1.5% Geopolymer, fulfilling the IRC:37–2018 requirements for pavement subgrade applications.
9) It is observed that the Cohesion (C) decreased by 37.38% on addition of 15% Copper Slag, and further decreased by 12.17% with the inclusion of 1.5% Geopolymer binder, while the angle of internal friction (ϕ) increased by 9.52% and 36.90%, respectively, signifying enhanced shear resistance and stability.

The combined use of 15% Copper Slag and 1.5% Geopolymer significantly improved the engineering characteristics of expansive soil by reducing its plasticity and swelling potential while enhancing its density, bearing capacity, and shear strength. The stabilized soil satisfies the strength requirements for pavement subgrade and represents a sustainable, eco-friendly, and cost-effective alternative to conventional stabilizers such as cement and lime.

Thus, the combination of 15% Copper Slag and 1.5% Geopolymer provides a sustainable and technically viable solution for stabilizing expansive soils for subgrade applications.

A. Viability

The treated Expansive Soil exhibited a California Bearing Ratio (CBR) value of **8.78%**, indicating satisfactory strength characteristics for subgrade applications. According to the provisions of *IRC: 37–2018*, the minimum required CBR value for a material to use as a subgrade should poses 8% in flexible pavement construction.

Since, the treated Expansive Soil achieved the CBR value is slightly above this requirement. Hence it fulfills the necessary performance criteria. Therefore, the treated Expansive Soil is suitable as a subgrade in flexible pavement systems.

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