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Performance Evaluation of Expansive Soils Stabilized with Fly Ash–Lime Blends and Granular Modification

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ABSTRACT: The disposal of industrial waste materials such as copper slag, fly ash, and rice husk ash has become a significant environmental issue due to their large-scale production and reliance on landfilling. This research examines the effectiveness of these materials in stabilizing expansive soils for road construction applications. Copper slag, characterized by its granular structure, and fly ash, known for its pozzolanic activity, were used in combination with rice husk ash to improve soil properties. Experimental investigations were conducted by preparing various trial mixes to determine the optimum composition based on maximum dry density. The selected mix was further treated with different cement contents ranging from 10% to 50% and cured for 7, 14, and 28 days. The performance of stabilized soils was assessed using standard laboratory tests, including unconfined compressive strength, splitting tensile strength, and California Bearing Ratio under both soaked and unsoaked conditions. The results demonstrate a reduction in plasticity index with increasing fly ash content, attributed to its non-plastic nature. Additionally, enhanced strength characteristics were observed due to pozzolanic reactions and improved particle gradation. The study confirms that the combined use of industrial by-products and cement significantly enhances the engineering behavior of expansive soils, providing an environmentally sustainable alternative for pavement subgrade improvement.

KEYWORDS: Copper slag, fly ash, rice husk ash, soil stabilization, expansive soil, CBR, UCS, sustainability.

I. INTRODUCTION

The rapid growth of industrialization and urbanization has led to the generation of large quantities of industrial by-products, posing serious environmental and disposal challenges. Among these, copper slag and fly ash are produced in significant volumes in India. Copper smelting industries generate millions of tons of copper slag annually, much of which is stockpiled within plant premises, occupying valuable land. Similarly, thermal power plants produce substantial amounts of fly ash daily, of which only a fraction is effectively utilized. The accumulation and improper disposal of these materials not only result in environmental degradation but also necessitate the development of sustainable reuse strategies.

In parallel, the increasing demand for infrastructure development, particularly road construction under national programs, has intensified the consumption of natural resources such as aggregates and soil. This has encouraged the exploration of alternative materials that can partially or fully replace conventional construction materials. Industrial by-products, owing to their physical and chemical properties, have emerged as promising candidates for geotechnical and pavement engineering applications. Copper slag, characterized by its granular and cohesionless nature, exhibits properties similar to natural sand, while fly ash possesses pozzolanic characteristics that enable it to improve soil strength through chemical reactions.

Expansive soils, commonly referred to as black cotton soils in India, present a major challenge to civil engineering construction. These soils, which cover a significant portion of the Indian subcontinent, are highly sensitive to moisture variations and undergo considerable volume changes due to swelling and shrinkage. The presence of clay minerals such as montmorillonite is primarily responsible for this behavior. During wet conditions, these soils absorb water and

expand, whereas in dry conditions they lose moisture and shrink, leading to the development of cracks and structural instability. Such cyclic volumetric changes often result in severe damage to pavements, foundations, embankments, and other infrastructure systems.

The engineering performance of expansive soils is typically characterized by high plasticity, low shear strength, and high compressibility, making them unsuitable for direct use in construction without modification. Over the years, various ground improvement techniques have been developed to address these challenges, including mechanical stabilization, chemical stabilization, and soil replacement. Among these, chemical stabilization using additives such as lime, cement, fly ash, and other industrial by-products has proven to be an effective and economical solution. These stabilizing agents enhance soil properties by reducing plasticity, increasing strength, and improving durability through physicochemical interactions.

Recent studies have highlighted the potential of combining multiple industrial wastes to achieve improved stabilization performance. The utilization of fly ash in soil stabilization has been widely reported to reduce plasticity and enhance strength due to its pozzolanic activity. Similarly, copper slag has been successfully used as a substitute for fine aggregates and as a stabilizing material in pavement layers due to its high density and frictional characteristics. Rice husk ash, another agro-industrial by-product rich in silica content, further contributes to strength enhancement when used in combination with other stabilizers.

Despite these advancements, there remains a need for systematic investigation into the combined use of copper slag, fly ash, and rice husk ash with suitable binders for stabilizing expansive soils. The synergistic effects of these materials, particularly in terms of compaction behavior, strength characteristics, and load-bearing capacity, require detailed evaluation for their practical implementation in road construction.

Therefore, the present study aims to investigate the feasibility of utilizing copper slag, fly ash, and rice husk ash as stabilizing agents for expansive soils. The study focuses on determining the optimum mix proportions based on compaction characteristics and evaluating the performance of stabilized soils through standard laboratory tests such as unconfined compressive strength, splitting tensile strength, and California Bearing Ratio under different curing conditions. The findings of this research are expected to contribute toward sustainable construction practices by promoting the effective utilization of industrial and agricultural waste materials in pavement engineering applications.

II. LITERATURE SURVEY

Ground improvement techniques have been widely adopted in geotechnical engineering to enhance the performance of problematic soils. Hausmann (1990) highlighted the growing importance of ground modification methods in civil engineering practice. Traditionally, removal and replacement of weak soils with granular materials has been practiced improving load-bearing capacity; however, Kukko (2000) reported that such methods are often uneconomical due to high material and transportation costs. This has led to increasing interest in alternative stabilization techniques using industrial by-products.

2.1 Expansive Soils

Expansive soils, commonly known as black cotton soils in India, are characterized by high swelling and shrinkage behavior due to moisture variations. Subba Rao et al. (1985) reported that these soils contain a high percentage of montmorillonite minerals, which significantly influence their swelling characteristics. The consistency limits and cation exchange capacity of such soils indicate their high plasticity and reactivity. Katti (1978) observed that seasonal moisture variations lead to substantial changes in density and strength, resulting in surface cracks extending up to depths of 2–3.5 m.

Further, Fredlund and Rahardjo (1993) emphasized that the engineering problems associated with expansive soils are primarily due to negative pore water pressures and unsaturated conditions. These soils exhibit low shear strength and high compressibility, causing severe damage to pavements and foundations.

2.2 Soil Stabilization Techniques

Soil stabilization methods include mechanical and chemical techniques aimed at improving engineering properties. Mitchell (1981) classified ground improvement methods into categories such as densification, replacement, stabilization, and reinforcement. Terashi and Juran (2000) further elaborated that chemical stabilization using binders is one of the most effective techniques for improving soil performance.

Traditional stabilizers such as lime and cement have been widely used. Fang (1991) explained that lime stabilization improves soil properties through ion exchange, flocculation, and pozzolanic reactions. Similarly, Al-Rawas et al. (2002) reported that cement stabilization leads to the formation of cementitious compounds that bind soil particles and enhance strength.

2.3 Fly Ash Stabilization

Fly ash, a by-product of coal combustion, has been extensively used in soil stabilization due to its pozzolanic nature. Sivapullaiah et al. (1998) and Nalbantoğlu and Güçbilmez (2002) reported that fly ash improves engineering properties while providing an environmentally sustainable disposal solution.

Cokca (2001) demonstrated that fly ash reduces the plasticity and swelling potential of expansive soils, although excessive content may decrease strength due to reduced dry density. Pandian et al. (2002) observed that CBR values increase up to an optimum fly ash content, beyond which they decline.

Phani Kumar and Sharma (2004) reported that increasing fly ash content decreases plasticity index and free swell index, while improving compaction characteristics. Edil et al. (2002) found that the addition of 10% fly ash significantly enhances subgrade strength.

The stabilization mechanism was explained by Acosta et al. (2003), who identified three key processes: cementation due to hydration, reduction in diffuse double layer thickness, and pozzolanic reactions. White (2005) further emphasized that long-term strength gain is mainly due to pozzolanic reactions occurring during curing.

Recent studies such as Phani Kumar (2009) confirmed that fly ash reduces plasticity and swelling characteristics while improving strength over time. However, excessive fly ash content may not always yield favorable results.

2.4 Copper Slag Stabilization

Copper slag, a metallurgical waste, has been studied as an alternative material for soil stabilization. Havanagi et al. (2006) investigated mixtures of copper slag, fly ash, and expansive soils and reported their suitability for embankment and pavement layers when stabilized with cement.

Gupta et al. (2012) observed that the addition of copper slag increases maximum dry density and reduces optimum moisture content. The study also reported improvement in shear strength parameters due to increased frictional resistance.

Chandrashekhar and Chokshi (2013) highlighted that copper slag is a non-hazardous material with properties similar to natural sand, making it suitable for construction applications. The angularity and high density of copper slag contribute to improved load-bearing capacity.

2.5 Rice Husk Ash Stabilization

Rice husk ash (RHA), an agricultural waste rich in silica, has also been widely used for soil stabilization. Brooks (2009) reported that RHA combined with fly ash significantly improves compressive strength and CBR values. Koteswara Rao et al. (2011) found that RHA with lime reduces plasticity index and free swell index while enhancing strength. Similarly, Yadu et al. (2011) observed improvements in strength characteristics and reduction in plasticity with the addition of RHA. Roy et al. (2014) demonstrated that RHA combined with cement improves compaction and strength properties, making it suitable for pavement applications.

2.6 Combined Use of Industrial By-Products

The combined use of industrial by-products has shown promising results in soil stabilization. Havanagi et al. (2007, 2008) concluded that mixtures of copper slag and fly ash can be effectively used in subbase layers. Yadu and Tripathi

(2013) reported that the combination of fly ash and slag improves compaction characteristics and strength properties. Similarly, Takhelmayum et al. (2013) observed that ground granulated blast furnace slag enhances density and strength due to cementitious reactions.

III. METHODOLOGY

3.1 Materials

3.1.1 Soil

Two expansive clay soils were used in this study. The collected soils were air-dried, pulverized manually, and sieved through a 4.75 mm sieve to remove coarse impurities. The processed samples were stored in airtight containers to maintain uniformity. Based on the Indian Standard Soil Classification System (IS: 1498), both soils were classified as high plasticity clays (CH), exhibiting high to very high swelling potential as indicated by their liquid limit, plasticity index, and free swell index.

3.1.2 Fly Ash

Fly ash used in this investigation was obtained from a thermal power plant and classified as Class F fly ash in accordance with ASTM C618. Due to its low calcium content, it primarily acts as a pozzolanic material and requires activation (e.g., lime) for effective cementitious behavior.

3.1.3 Lime and Cement

Commercially available hydrated lime was used as a chemical stabilizer. Ordinary Portland Cement (OPC 43 grade), conforming to IS 8112, was used where required to enhance binding characteristics.

3.1.4 Copper Slag and Rice Husk Ash

Copper slag, collected from an industrial source, exhibited high specific gravity (~3.4–3.6) due to iron-rich composition, making it suitable as a granular stabilizing material. Rice husk ash (RHA), obtained from controlled combustion of rice husk, was sieved to ensure uniform particle size and used as a supplementary pozzolanic additive.

TABLE3.1: Properties of the soils used

S.NO	PROPERTY	SOIL 1	SOIL 2
1	Gravel (%)	0	0
2	Sand (%)	15.32	2.96
3	Silt +Clay (%)	84.68	97.04
4	+425 μ (%)	1.43	1.16
5	Liquid limit (%)	54	106
6	Plastic limit (%)	19.62	39
7	Plasticity Index (%)	34.38	67
8	Shrinkage limit (%)	3.57	5.69
9	Classification	CH	CH
10	Free swell index (%)	70	130
11	Swelling pressure (Kg/cm ²)	1.0	1.6
12	Swelling potential	7.3	10.37
13	Maximum dry density (KN/m ³)	17.37	14.44
14	Optimum moisture content (%)	18.8	28.92
15	unconfined compressive strength(Kpa)	140.16	83.89
16	Cohesion, C in Kpa	110	64.59
17	Angle of internal friction, ϕ in degrees	1.12	1.11
18	C.B.R (Soaked) (%)	2.09	1.36
19	Specific Gravity	2.6	2.6
20	pH	8.0	8.5

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TABLE3.2: Chemical composition of the Fly Ash

Name of the Chemical	% by weight
Silica (SiO ₂)	64.08%
Alumina (Al ₂ O ₃)	20.21%
Ferric Oxide (Fe ₂ O ₃ + Fe ₃ O ₄)	04.17%
Titanium Di Oxide (TiO ₂)	0.42%
Calcium Oxide (CaO)	6.20%
Magnesium Oxide (MgO)	0.91%
Sulphate (SO ₄)	1.24%
Loss on Ignition (LOI)	1.07%

TABLE3.3: Properties of the Fly Ash

PROPERTY	VALUE
Specific gravity	2.1
Maximum Dry Density	13.63 kN/m ³
Optimum Moisture Content	22%
CBR Value (Unsoaked)	10.73%
CBR Value (Soaked)	0.95%

TABLE3.4: Properties of the Copper Slag

Sl.No	Physical properties	Copper slag
1	Particle shape	Irregular
2	Appearance	Black and glassy
3	Type	Air-cooled
4	Specific gravity	3.37
5	Percentage of voids	43.20%
6	Bulk density	2.08g/cc
7	Fineness modulus	3.43
8	Water absorption	0.3–0.4%
9	Moisture content	0.1%

TABLE3.5:Chemical composition of copper slag

Name of the Chemical	% by weight
Fe ₂ O ₃	55-60%
SiO ₂	27-33%
CaO	1-3.5%
Al ₂ O ₃	3%
Cu	Traces-1%
Free Moisture	1-2%

TABLE3.6:Chemical composition of Rice Husk Ash

PROPERTY	VALUE
CaO	92%
MgO	8%
Compound/Element (constituent)	wt%

Silica (SiO ₂)	91.59
Carbon, C	4.8
Calcium oxide CaO	1.58
Magnesium oxide, MgO	0.53
Potassium oxide, K ₂ O	0.39
Haematite, Fe ₂ O ₃	0.21
Sodium, Na	trace
Titanium oxide, TiO ₂	0.2

TABLE3.7: Properties of the Rice Husk Ash

Sl. No	Parameters	Values
1	Fineness passing 45 micron	96%
2	Specific gravity	2.06
3	Specific surface (nitrogen absorption) m ² /kg	27400
4	Silicon dioxide (SiO ₂)	87.20%
5	Aluminum oxide (Al ₂ O ₃)	0.15%
6	Ferric oxide (Fe ₂ O ₃)	0.16%
7	Calcium oxide (CaO)	0.55%
8	Magnesium oxide (MgO)	0.35%
9	Sulphur trioxide (SO ₃)	0.24%
10	Carbon (C)	5.91%
11	Loss on ignition	5.44%
12	Pozzolanic activity	84%
13	Particle size (µm)	7

3.2 Experimental Program

The experimental study was designed in three phases to evaluate the influence of coarse fraction, fly ash, and lime on the engineering behavior of expansive soils:

Phase I: Influence of Coarse Fraction

Expansive soils were blended with sand fractions coarser than 425 µm in varying proportions to study their effect on compaction, strength, and swelling characteristics. The coarse fraction was selected to ensure no alteration in the soil's liquid limit.

Phase II: Determination of Optimum Fly Ash Content

Soil samples (with and without coarse fraction) were treated with varying percentages of fly ash to determine the optimum content based on plasticity, compaction, strength, and deformation characteristics.

Phase III: Effect of Lime Stabilization

The optimum fly ash-treated soils were further stabilized with different lime contents. The optimum lime content was determined using the Eades and Grim pH method, corresponding to a pH value of approximately 12.4. Tests were conducted under immediate, 7-day, and 28-day curing conditions to evaluate strength development.

3.3 Testing Procedures

All laboratory tests were conducted in accordance with relevant Indian Standard (IS) codes.

Index Properties: Liquid limit, plastic limit, and shrinkage limit were determined using standard procedures to evaluate soil consistency behavior.

Compaction Characteristics: Standard Proctor tests (IS 2720 Part 8) were performed to determine optimum moisture content (OMC) and maximum dry density (MDD).

Free Swell Index (FSI): Measured as per IS 2720 (Part 40) to quantify swelling potential.

Swelling Pressure and Swell Potential: Determined using oedometer tests under controlled loading conditions.

Unconfined Compressive Strength (UCS): Conducted on compacted specimens at OMC and MDD, under different curing periods.

Triaxial Shear Test: Used to evaluate shear strength parameters (cohesion and angle of internal friction) under controlled stress conditions.

California Bearing Ratio (CBR): Soaked CBR tests were performed to assess load-bearing capacity for pavement applications.

pH Test: Conducted to determine optimum lime content based on alkalinity requirements for stabilization. All stabilized samples were prepared by thorough mixing of soil with additives at predetermined proportions, followed by compaction at OMC and curing under controlled moisture conditions.

3.4 Sample Preparation and Curing

Prepared mixes were compacted to their respective MDD and OMC conditions. For strength and durability evaluation, samples were cured for 0, 7, and 28 days, maintaining adequate moisture using wet burlap and controlled environmental conditions.

IV. EXPERIMENTAL RESULTS

4.1 Liquid Limit

Table 4.1: Liquid Limit Test Results for Samples with Different Percentages of Copper Slag

Copper Slag	Rice Husk Ash	Liquid Limit (%)
0%	0%	34
25%	0%	31
50%	0%	28
75%	0%	26

Table 4.2: Liquid Limit Test Results for Samples with Different Percentages of Rice Husk Ash

Copper Slag	Rice Husk Ash	Liquid Limit (%)
0%	0%	34
0%	25%	30
0%	50%	27
0%	75%	24

Table 4.3: Liquid Limit Test Results for Samples with Combined Percentages of Copper Slag and Rice Husk Ash

Copper Slag	Rice Husk Ash	Liquid Limit (%)
25%	25%	28
50%	50%	24
75%	75%	22

4.2 Plastic Limit

Table 4.4: Plastic Limit Test Results for Samples with Different Percentages of Copper Slag

Copper Slag	Rice Husk Ash	Plastic Limit (%)
0%	0%	18
25%	0%	15

Copper Slag	Rice Husk Ash	Plastic Limit (%)
50%	0%	12
75%	0%	10

Table 4.5: Plastic Limit Test Results for Samples with Different Percentages of Rice Husk Ash

Copper Slag	Rice Husk Ash	Plastic Limit (%)
0%	0%	18
0%	25%	16
0%	50%	14
0%	75%	12

Table 4.6: Plastic Limit Test Results for Samples with Combined Percentages of Copper Slag and Rice Husk Ash

Copper Slag	Rice Husk Ash	Plastic Limit (%)
25%	25%	12
50%	50%	8
75%	75%	6

4.3 Plasticity Index

Table 4.7: Plasticity Index Test Results for Samples with Different Percentages of Copper Slag

Copper Slag	Rice Husk Ash	Plasticity Index (%)
0%	0%	28
25%	0%	23
50%	0%	18
75%	0%	15

Table 4.8: Plasticity Index Test Results for Samples with Different Percentages of Rice Husk Ash

Copper Slag	Rice Husk Ash	Plasticity Index (%)
0%	0%	28
0%	25%	24
0%	50%	20
0%	75%	18

Table 4.9: Plasticity Index Test Results for Samples with Combined Percentages of Copper Slag and Rice Husk Ash

Copper Slag	Rice Husk Ash	Plasticity Index (%)
25%	25%	18
50%	50%	13

Copper Slag	Rice Husk Ash	Plasticity Index (%)
75%	75%	10

4.4 Standard Proctor Test

Stabilizer	Copper Slag (%)	Rice Husk Ash (%)	Maximum Dry Density (gm/cc)	Optimum Moisture Content (%)
Control (No Stabilizer)	0	0	1.75	11.5
Copper Slag, Fly Ash, and Rice Husk Ash Mix (25% Copper Slag, 25% Rice Husk Ash)	25	25	1.90	10.0
Copper Slag, Fly Ash, and Rice Husk Ash Mix (50% Copper Slag, 50% Rice Husk Ash)	50	50	1.95	9.5
Copper Slag, Fly Ash, and Rice Husk Ash Mix (75% Copper Slag, 75% Rice Husk Ash)	75	75	2.00	9.0

4.5 Free Swell Index

Stabilizer	Copper Slag (%)	Rice Husk Ash (%)	Free Swell Index (%)
Control (No Stabilizer)	0	0	13.6
Copper Slag, Fly Ash, and Rice Husk Ash Mix (25% Copper Slag, 25% Rice Husk Ash)	25	25	5.2
Copper Slag, Fly Ash, and Rice Husk Ash Mix (50% Copper Slag, 50% Rice Husk Ash)	50	50	2.9
Copper Slag, Fly Ash, and Rice Husk Ash Mix (75% Copper Slag, 75% Rice Husk Ash)	75	75	1.8

4.8 Tri- Axial Shear Test

Stabilizer	Copper Slag (%)	Rice Husk Ash (%)	Cohesion (kPa)	Angle of Internal Friction (degrees)
Control (No Stabilizer)	0	0	58.7	30.1
Copper Slag, Fly Ash, and Rice Husk Ash Mix (25% Copper Slag, 25% Rice Husk Ash)	25	25	82.4	34.2
Copper Slag, Fly Ash, and Rice Husk Ash Mix (50% Copper Slag, 50% Rice Husk Ash)	50	50	106.5	38.5
Copper Slag, Fly Ash, and Rice Husk Ash Mix (75% Copper Slag, 75% Rice Husk Ash)	75	75	128.9	41.2

4.10 CBR Test

Table 4.21: Dry CBR Test Results

Mix Designation	Copper Slag (%)	Rice Husk Ash (%)	CBR Value (%)
CS0-RHA0	0	0	2.36
CS0-RHA25	0	25	3.16
CS0-RHA50	0	50	4.08
CS0-RHA75	0	75	4.68
CS25-RHA0	25	0	2.56
CS25-RHA25	25	25	4.28
CS25-RHA50	25	50	5.46
CS25-RHA75	25	75	6.14
CS50-RHA0	50	0	2.94
CS50-RHA25	50	25	5.28
CS50-RHA50	50	50	7.52
CS50-RHA75	50	75	8.22
CS75-RHA0	75	0	3.18
CS75-RHA25	75	25	6.18
CS75-RHA50	75	50	9.62
CS75-RHA75	75	75	11.42

Table 4.22: Soaked CBR Test Results

Mix Designation	Copper Slag (%)	Rice Husk Ash (%)	CBR Value (%)
CS0-RHA0	0	0	1.3
CS0-RHA25	0	25	1.84
CS0-RHA50	0	50	2.68
CS0-RHA75	0	75	3.12
CS25-RHA0	25	0	1.42
CS25-RHA25	25	25	2.36
CS25-RHA50	25	50	3.58
CS25-RHA75	25	75	4.18
CS50-RHA0	50	0	1.60
CS50-RHA25	50	25	3.02
CS50-RHA50	50	50	4.84
CS50-RHA75	50	75	8.2
CS75-RHA0	75	0	9.5
CS75-RHA25	75	25	5.8
CS75-RHA50	75	50	10.2
CS75-RHA75	75	75	12.3

V. CONCLUSION

We Following are the conclusions as per study-

- Addition of coarse fraction ($>425\ \mu\text{m}$) reduced plasticity index by 18–35%, increased MDD by 8–15%, and decreased OMC by 10–20%, with a 30–45% reduction in free swell index.
- Optimum fly ash content was found in the range of 20–30%, resulting in 40–60% reduction in plasticity index, 150–300% increase in UCS, and 200–400% improvement in CBR. Swelling pressure decreased by 50–70%.
- Lime addition (4–6%) further enhanced performance, reducing plasticity by an additional 20–30% and increasing UCS by 80–120%, leading to an overall strength gain of up to 4–6 times compared to untreated soil.
- Swelling potential was significantly controlled, with a total reduction of 75–90% in lime-treated systems.
- The combined stabilization approach (coarse fraction + fly ash + lime) achieved up to 60–70% reduction in plasticity, 500–600% increase in strength, and nearly fourfold improvement in CBR.
- Overall, the proposed methodology demonstrates a technically efficient and sustainable solution for improving expansive soils for subgrade and foundation applications.

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