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A Review on Design of Rigid Pavements of Rural Roads using Copper Slag as Additive

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Abstract: This study investigates the use of copper slag as an additive in soil stabilization for rural road subgrades. Laboratory experiments were conducted to evaluate the effects of mixing copper slag with lime. The study examined changes in Atterberg limits and California Bearing Ratio (CBR) resulting from these mixtures. Based on the improved CBR values, rigid pavement designs were developed in accordance with IRC SP 62-2014 guidelines. The performance of the stabilized soils was analyzed for lime-copper slag.

IndexTerms: Waste utilization, ground improvement, design. -

I. INTRODUCTION

Expansive soils are known for their undesirable engineering behavior due to their tendency to undergo significant volume changes in response to moisture fluctuations. These soils exhibit high strength in dry conditions, but their strength drastically reduces upon water absorption. The primary cause of this behavior is the presence of clay minerals such as Montmorillonite, which absorb water and expand, leading to swelling pressures that can damage overlying structures, especially pavements.

In India, expansive soils like black cotton soil are widespread and pose a major challenge in rural road construction. Stabilization of these soils is essential to ensure long-term performance and durability of pavements. Traditional stabilizers such as lime and cement have been widely used to improve the strength and reduce the plasticity of expansive soils. However, the high cost and environmental impact of these materials necessitate the exploration of alternative or supplementary stabilizers.

Copper slag, a byproduct of the copper smelting process, has emerged as a promising material for soil stabilization. India, being one of the major copper-producing countries, generates large quantities of copper slag annually. Typically, copper slag contains 25–40% amorphous silica, which provides pozzolanic properties when combined with lime or cement. However, its disposal remains an environmental concern, with a significant portion being dumped in unauthorized sites.

Utilizing copper slag in ground improvement applications not only offers a sustainable solution for industrial waste management but also has the potential to enhance the engineering properties of weak soils. Previous studies have indicated that copper slag, when blended with lime, can improve the bearing capacity and reduce the plasticity of expansive soils.

This study aims to evaluate the effectiveness of copper slag as an additive in lime stabilized expansive soils. Laboratory investigations were conducted to assess the variations in Atterberg limits and California Bearing Ratio (CBR) values for different mix proportions. Based on the improved CBR results, rigid pavement design were carried out in accordance with IRC SP 62:2014, respectively.

II. LITERATURE REVIEW

Expansive soils are widely recognized for their problematic behavior due to their high shrink–swell potential. The presence of clay minerals, particularly Montmorillonite, makes these soils highly susceptible to volumetric changes with fluctuations in moisture content. This poses a significant challenge for infrastructure built on such subgrades, especially in regions with seasonal rainfall. Consequently, various soil stabilization techniques have been explored to mitigate the adverse effects of expansive soils, among which chemical stabilization using lime and cement has proven effective. In recent decades, environmental sustainability and material scarcity have driven a shift toward the use of industrial by-products and waste materials in civil engineering applications. The reuse of such materials not only addresses environmental concerns but also offers economic benefits and resource conservation. One such industrial by-product is copper slag, generated during the smelting and refining of copper. Several researchers have investigated the applicability of copper slag in highway and geotechnical engineering. Al-Jabri et al. (2002) and

Yogendra K. Tandel reported the feasibility of using copper slag in road base construction, railroad ballast, and engineered fill. Moura et al. (2000) conducted a life-cycle analysis of metal industry slag in road construction and concluded its reuse as both technically and environmentally viable. Das et al. (1993) noted that copper slag contains significant quantities of Fe_2O_3, SiO_2, and CaO, which make it amenable to chemical stabilization. Mobasher et al. (1996) observed that partial replacement of Portland cement with copper slag increased the compressive strength of concrete mixes, highlighting its potential in concrete pavement applications. Collins and Cieliesk (1994) presented findings from the Transportation Research Board regarding the successful use of copper slag aggregates in hot mix asphalt (HMA) pavements. Moura et al. (1999) further verified that the physical characteristics of copper slag from Bahia, Brazil, were comparable or superior to conventional construction materials. A notable contribution by R. Tixier investigated the hydration and pozzolanic activity of copper slag in the presence of lime and cement. The study involved two types of cementitious pastes: one with 95% copper slag and 5% hydrated lime, and another with 85% copper slag, 10% micro silica, and 5% lime. Through semi-quantitative X-ray diffraction over a 180-day period, the study observed a reduction in calcium hydroxide peaks, confirming pozzolanic reactions and the material's long-term stabilization potential. Copper slag has also been explored in bituminous pavement construction. Asad Iqbal and M. Nadeem studied its use in Hot Mix Asphalt (HMA), emphasizing its potential to improve interlocking and compaction characteristics. Pundhir et al. (2005) employed copper slag as a fine aggregate (up to 40%) in Marshall-designed mixes, reporting improved volumetric and mechanical properties. Havanagi et al. (2012) studied the feasibility of using copper slag, zinc slag, and steel slag in sub-base, base, and bituminous layers. Their results supported partial replacement of fine aggregates with these industrial wastes. Kajal et al. (2007) further enhanced bituminous mixes with waste plastics and varying percentages of copper slag, achieving favorable outcomes in terms of binder content optimization and mix performance. Debashish Kar et al. (2014) investigated the influence of cement as filler in bituminous mixes, observing increased Marshall Stability and unit weight with optimal bitumen content, further validating the compatibility of copper slag with traditional additives. Mobasher et al. (1996) concluded that residual metallic content in copper slag enhances the stability of bituminous mixes when used as fine aggregate. Despite these numerous studies, most existing research has focused either on the mechanical performance of copper slag-treated soils or its use as a partial aggregate substitute in bituminous mixes. However, limited attention has been given to the pavement design aspect post-stabilization using copper slag. Thus, the present study aims to fill this gap by comprehensively analyzing the use of copper slag as an additive in lime stabilized expansive soils. The study includes detailed laboratory evaluation, pavement design following IRC guidelines.

III. METHODOLOGY

Laboratory experiments were designed to assess the physical and mechanical properties of soil stabilized with varying proportions of lime and copper slag. Comprehensive testing was carried out to determine the optimum mix designs and their suitability for rigid pavement construction based on Indian Roads Congress (IRC) guidelines.

Soil Sample Preparation

The soil used in this study was collected from the project site and initially processed by pulverizing with a wooden mallet to break down any lumps. The sample was then air-dried, sieved through a 4.75 mm IS sieve, and oven-dried at 105℃ for 24 hours to remove moisture. This prepared soil was used for subsequent physical and engineering property tests.

Laboratory Testing of Soil

A series of tests were performed to determine the properties of the expansive soil, including grain size distribution, Atterberg limits, specific gravity, differential free swell index, IS light compaction test, unconfined compressive strength (UCS), and California Bearing Ratio (CBR) tests. Copper slag was also characterized by specific gravity, grain size distribution, and compaction properties.

Stabilization Procedure

Lime were sieved to remove lumps and then mixed separately with soil in increments of 2% by weight, ranging from 2% to 12%. Each soil-lime mixture was uniformly blended to ensure consistent coverage. The mixes were compacted in molds at their respective Optimum Moisture Content (OMC) and to the required thickness for testing.

Determination of Optimum Binder Content

Unconfined compressive strength (UCS) and pH tests were conducted on soil samples stabilized with varying percentages of lime. The optimum content of lime was identified as the percentage at which the UCS was maximized and the pH was approximately 12.4, indicating effective stabilization.

Preparation of Copper Slag Mixtures

Using the optimum lime contents determined, copper slag was added to the stabilized soil in increments of 2%, forming two sets of mixes: Soil–Optimum Lime–Copper Slag the detailed mix proportions are provided in Table 3.1.

Table 3.1: Various mixes considered for study

Sl.no	Name of the mix	Sl.no	Name of the mix
1a	soil-8%lime-2%copper slag	1d	soil-8%lime-8% copper slag
1b	soil-8%lime-4% copper slag	1e	soil-8%lime-10% copper slag
1c	soil-8%lime-6% copper slag	1f	soil-8%lime-12% copper slag

Curing and Testing of Stabilized Mixes

All the prepared samples were cured for 7 days under controlled conditions by storing them in a desiccator submerged in water. Post-curing, unconfined compressive strength (UCS) and California Bearing Ratio (CBR) tests were conducted to evaluate the mechanical behavior of the mixes. Additionally, samples were powdered and passed through a 425-micron sieve for testing of Atterberg limits (liquid limit, plastic limit, plasticity index, shrinkage limit), pH, and differential free swell index as per IS standards.

Pavement Design

Based on the results of the CBR tests, Atterberg limits, and traffic load estimates for a 5-year design period covering both harvesting and non-harvesting seasons, pavement designs were developed according to Indian Roads Congress (IRC) guidelines. Flexible pavements were designed for rigid (cement concrete) pavements as per IRC 62:2014.

IV. RESULTS AND DISCUSSIONS

Results obtained from various studies conducted on various mixes are as follows. Various tests have been done on expansive soil, stabilizing with using copper slag as additive. The results obtained are as follows.

4.1. Physical and Engineering properties of expansive soil

The physical and engineering properties of expansive soil are listed in the Table 5.1. It can be observed that the soaked CBR of the soil considered was 0.85% is very low (< 2% recommended as per IRC SP: 72-2015) [15] and Differential Free Swell Index (DFSI) was 110%, very high (> 50%, (IS-.2911 Part III-1980)).

Table 4.1 Physical and Engineering properties of expansive soil

S.no	Properties	Value
1	specific gravity	2.55
2	Particle Size distribution	
	a) Gravel (%)	0.9
	b) Sand (%)	16.8
	c)Clay (%)	82.3
3	Liquid limit (%)	52
4	Plastic limit (%)	26.09
5	Plasticity Index (%)	25.91
6	IS Classification of Soil	CH
7	Maximum Dry Density(kN/m^3)	14.4
8	Optimum Moisture Content (%)	23
9	Unconfined Compression test(kN/m^2)	53.77
10	Differential free swell index (%)	120
11	Shrinkage Limit (%)	11.35
12	Soaked CBR value (Compacted at OMC) (%)	0.85
13	Unsoaked CBR value (Compacted at OMC) (%)	3

From the SEM image of soil (Figure.4.1), it can be observed that the texture of soil contains dispersed fabric in natural state and flaky like structure. In general soil that has flaky structure possesses less strength.

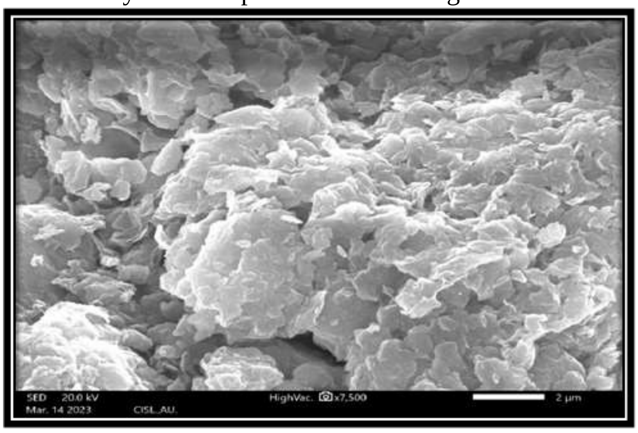

Fig:4.1 SEM image of soil without treatment Physical & Chemical properties of copper slag

Table – 4.2 Physical properties of Copper Slag.

Property	Value
Color	Black
Sp.gr (g/cc)	3.5
Grain shape	Angular
OMC (%)	16.11
MDD (g/cc)	2.14

Table – 4.3 Chemical Properties of Copper Slag.

S. No	Constituents	Percentage (%)
1	Cu	0.42-4.6
2	Fe O	29-40
3	SiO2	30-40
4	CaO	<11
5	AL2O3	<10

Compaction test was conducted on Copper Slag to determine optimum moisture content.. It can be seen that from (Table 4. 2), the specific gravity of Copper Slag is lower than that of soil. While optimum moisture content is very less stating that there is less affinity of copper slag towards water. Chemical composition of Copper Slag was studied at Indian Institute of chemical technology, Hyderabad. From the chemical analysis (Table 4.3), it was observed that silica & Iron (SiO2 & FeO) is the major compound of and oxides of calcium, Aluminum as minor compounds. High amount of Silica & Iron makes Copper Slag highly siliceous & alumina which is also named as pozzolana. But Copper Slag lacks cementitious properties.

4.2. Engineering Properties of Soil stabilized with lime

Compaction and unconfined strength have been conducted on soil stabilized with lime in increments of 2% for optimum lime identification.

Table – 4.4 Engineering properties of Soil with increasing percentage of lime.

SI.NO	% OF lime	OMC (%)	MDD (gm/cc)	UCS (kN/m^2)
1	2	24	1.435	37.7
2	4	25	1.426	46.1
3	6	25.9	1.425	65.6
4	8	26	1.421	89.2
5	10	24	1.450	78.5
6	12	23.9	1.510	61.3

From Table 4.4 Initial increase in OMC values with lime may be attributed to the development of flocculated structure which resists the compaction effort and the decrease in dry density may be attributed due to less occupation of less space by soils because of change in soil structure. Hence from the above results of Table 5.4 optimum lime percentage was 8%.

4.3. MDD, OMC, CBR, PI variations with different percentages of copper slag with optimum Lime

Compaction test has been conducted on different percentages of copper slag with optimum Lime. CBR tests were conducted on different percentages of copper slag with optimum Lime at wet of optimum, in addition to that Liquid limit and plastic limit studies are conducted on different percentages of copper slag with optimum Lime and the results of various tests obtained are given in Table 4.5 below

Table 4.5: Values of MDD, OMC, CBR, PI for Soil-Lime-Copper slag mixes

MIX	MDD (gm/cc)	PI	CBR (%)	OMC (%)
Soil+8%Lime+2%CS	1.400	33	4.5	31.6
Soil+8%Lime+4%CS	1.420	27	7.43	24.5
Soil+8%Lime+6%CS	1.460	24	13.9	20.8
Soil+8%Lime+8%CS	1.520	15	15.6	12.78
Soil+8%Lime+10%CS	1.480	N. P	21.4	29
Soil+8%Lime+12%CS	1.420	N. P	19	36

The analysis of engineering properties reveals that the initial increase in Maximum Dry Density (MDD) can be attributed to the incorporation of copper slag particles, which are relatively heavier and denser than soil particles. However, with further addition of copper slag, a decline in MDD is observed. This reduction may be due to the segregation of coarser copper slag particles within the soil matrix, leading to a less compact arrangement. Concurrently, a decrease in Optimum Moisture Content (OMC) is noted at early stages, likely resulting from the inclusion of coarse-grained copper slag particles, which possess minimal water absorption capacity. In soil–lime–copper slag blends, a progressive reduction in dry density is recorded with increasing copper slag content. This behavior can be attributed to the lower specific gravity of copper slag compared to that of native soil particles. Moreover, the chemical interaction between lime and soil initiates Base Exchange processes, resulting in flocculation and aggregation of soil particles. These microstructural transformations elevate the void ratio, thereby diminishing the overall dry density of the stabilized mixture. The enhancement in California Bearing Ratio (CBR) values across all treated mixes can be primarily ascribed to accelerated pozzolanic activity. Lime, known for its high reactivity, contributes significantly to these reactions. Additionally, the introduction of copper slag increases the availability of reactive silica and alumina in the system, promoting the formation of cementitious products such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These compounds play a crucial role in the development of strength and stiffness within the treated soil.

4.4. **Design of Cement Concrete Pavement According to IRC: SP-62- 2014.**

Since the traffic is 64CVPD the traffic will be shifted to Case 2 of excel sheet analysis and our zone will be zone III. Based on CBR K values are calculated and assuming joint spacing to be 2.5m. From Table 16-19 the design has been made using Excel sheet of IRC-SP-62-2014, it was observed that the thickness of the pavement remains the same for CBR> 4.5 Since K of design is influenced by CBR. But K values have negligible influence on thickness of cement concrete pavement.

case 1: design traffic is <50 CVPD case 2: traffic is in between 50 to 150 CVPD case 3: traffic is >150 CVPD	
ENTER THE DATA	
Case 1/2/3	2
temperature zone (1 to 6)	1
modulus of the subgrade reaction, k M pa/r	37
elastic modulus of concrete E, M pa	30000
Poisson ratio of concrete, μ	0.15
temperature differential, Δ t , o C	12.8
modulus of rupture of concrete, F cr	4.22

tyre(1-single/2-dual)	1
spacing of wheels Sd(mm)	310
wheel load, P KN	50
tyre pressure, q M pa	0.8
radius of contact, a(mm)	141.0474
trial thickness, h m	0.175
No of commercial vehicles per day	300

transverse joint spacing, m	2.5
ratio of L/I	3.204
coefficient of thermal expansion	0.00001
correction factor C	0.2593
design life of pavement, yrs	20
rate of increase o traffic	0.06
truck with 50 KN wheel load, %	10

RESULTS FOR WHEEL LOAD AND TEMPERATURE	
CASE 2	
temperature stress at edge, M pa	0.0096
wheel load stresses at edge, M pa	4.008
total stresses, σ, M pa	4.0183
design is	safe

ENTER THE DATA	
CASE1/2/3	2
Temperature zone (1 to 6)	1
modulus of subgrade reaction, k, M pa/m	38
elastic modulus of concrete E, M pa	30000
Poisson ratio of the concrete, μ	0.15
temperature differential, Δ t, o C	12.7

Tyre (1-single /2- dual)	1
spacing of wheels Sd(mm)	310
wheel load P KN	50
Tyre pressure, q M pa	0.8
radius of contact, a (mm)	141.04
trial thickness, h m	0.17
no of commercial vehicles per day	300

V. CONCLUSION:

- The plasticity index of the soil decreased with increasing copper slag content, both in soil–copper slag and soil–lime–copper slag mixes. This reduction is attributed to the disruption of the double-diffused layer and the void-filling effect of copper slag particles, leading to a less plastic and more granular soil matrix.
- In soil–lime–copper slag mixtures, the dry density exhibited varying trends. An initial increase in dry density was observed, likely due to the inclusion of heavier materials such as stone dust. Conversely, in mixes where copper slag was used independently, a reduction in dry density was noted, owing to the lower specific gravity and lighter weight of copper slag compared to native soil particles.

- The California Bearing Ratio (CBR) improved across all treated mixes. This enhancement is attributed to the formation of cementitious compounds, such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), resulting from pozzolanic reactions and cation exchange processes. These reactions contribute to improved particle bonding and a flocculated soil structure.
- The combined use of lime and copper slag proved effective in improving the geotechnical properties of expansive soils. This method offers a cost-effective and sustainable solution, particularly suited for low-volume rural roads constructed with cement concrete pavements. It also presents advantages in terms of both initial construction efficiency and reduced maintenance requirements.

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