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Stabilisation of Expansive soil Subgrade with Copper slag and Zycobond nano-polymer: An Experimental and Regression-based Assessment

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Abstract: - Expansive soils in the Konaseema region of Andhra Pradesh, India, swell and shrink with seasonal moisture change and is a persistent cause of pavement distress. This study evaluates copper slag (CS), an industrial by-product of copper smelting, and Zycobond, an acrylic copolymer nano-polymer, as combined stabilisers for an expansive clay subgrade. The untreated soil was a high-plasticity clay (CH) with a liquid limit of 67.6%, a plasticity index (PI) of 39.7%, a differential free swell (DFS) of 90% and a soaked California Bearing Ratio (CBR) of 1.41%. Copper slag tested for various percentages between 0–22% identified 18% as the optimum, raising soaked CBR to 4.66% and lowering PI to 23.2%. Zycobond dosages of 0.5–2.0% were then added to the 18% CS mix. The optimum dosage of 1.5% raised soaked CBR to 8.11% (a 475% gain over the untreated soil), reduced PI by 68% to 12.7%, reduced DFS from 90% to 48%, and increased maximum dry density from 1.58 to 1.87 g/cc. Linear and quadratic regression models described the dosage–response relationships (R^2 up to 0.998). Laboratory static plate load tests on model foundation beds showed that ultimate bearing pressure rose from 720 to 1460 kPa while settlement at failure fell from 3.12 to 1.78 mm. The combined treatment lifts the soaked CBR above the 8% subgrade minimum in IRC:37-2018 while making use of an industrial waste stream.

Keywords: Expansive soil, Copper slag, Zycobond, Nano-polymer, Subgrade stabilisation, Plate load test.

1. Introduction

Expansive soils change volume markedly with moisture content: they swell on wetting and shrink on drying. The behaviour is governed mainly by clay mineralogy. Montmorillonite, a member of the smectite group, is the most swell-active common mineral, because water is drawn between its layers and forces the clay plates apart [1], [2]. Soils with a liquid limit above 50% and a plasticity index above 30% are generally regarded as having expansive clay mineralogy. Smectite-rich Vertisols cover roughly 240 million ha worldwide, of which about 73 million ha lie in India [3].

Alternating swelling and shrinkage create cracks lightly loaded structures such as pavements, canal linings, boundary walls and shallow foundations. Beneath a road, the subgrade heaves in wet periods and shrinks in dry periods, and the repeated cycles produce cracking, surface irregularity and rutting. Remedial measures include soil replacement, pre-wetting, moisture barriers, cohesive non-swelling (CNS) layers, under-reamed piles, reinforcement and chemical stabilisation with lime or cement. Several of these are slow, costly or difficult to execute. Pre-wetting the highly plastic clays takes a long time, moisture barriers are hard to construct reliably, lime treatment suffers from pulverisation and mixing problems, and replacement requires suitable fill to be hauled over long distances.

Stabilisation with industrial by-products has therefore attracted sustained interest, because it can improve the subgrade and reduce the volume of material to be sent to landfill. Copper slag is generated at a rate of about 2–3 tonnes per tonne of copper produced and is a black, glassy, coarse granular material [4]. It has been investigated as fill, as a replacement for fine aggregate and as a soil additive [5]. Gupta et al. [6] reported improved strength of clayey soil stabilised with copper slag. Kavisri et al. [7] found that a blend of 70% clay with copper slag and ground granulated blast-furnace slag met subgrade requirements. Goud and Laya [8] reduced the free swell of black cotton soil from 100% to 20.4% using copper slag and rice husk ash. Parvathy and Nelson [9] and Patel et al. [10] examined copper slag together with lime and with fly ash respectively. In most of these studies copper slag acts as a granular, non-plastic diluent that densifies the soil and lowers its plasticity, but it contributes little cohesion or bonding. A similar pattern was reported by Sai Ram et al. [11] for a Kakinada marine clay: a non-plastic granular additive (foundry sand) at its optimum content reduced plasticity and raised the soaked CBR to 5.83%, which was still below the 8% subgrade requirement, so a chemical binder was needed to close the gap.

Nano-polymer soil stabilisers offer a complementary mechanism. Zycobond is a sub-micron acrylic copolymer emulsion with a particle size below 90 nm. Its very large surface area provides many contact points for bonding with soil particles, and it is reported to improve load-bearing capacity, flexibility, water resistance and resistance to erosion. Studies of the related Terrasil and Zycobond products have reported lower free swell and higher density and strength in treated soils [12]. Reported results for combined copper slag–Zycobond treatment of expansive soil, particularly with model foundation-bed verification, are scarce.

This paper investigates the combined use of copper slag and Zycobond to improve an expansive soil from Ramachandrapuram, Dr. B. R. Ambedkar Konaseema District, for use as a pavement subgrade. The specific objectives are: (i) to characterise the index and engineering properties of the untreated soil; (ii) to identify the optimum copper slag content from DFS, Atterberg limits, compaction, soaked CBR and triaxial results; (iii) to establish the optimum Zycobond dosage for the copper slag-treated soil; (iv) to express the dosage–response relationships as regression equations; and (v) to verify the performance of the optimum mix in laboratory static plate load tests on model foundation beds. The approach follows that of Sai Ram et al. [11], who combined a granular industrial waste with a chemical binder and verified the optimum mix in laboratory model plate load tests.

2. Materials

2.1 Expansive soil

Natural expansive soil was collected from Ramachandrapuram, Dr. B. R. Ambedkar Konaseema District, Andhra Pradesh, at a depth of 0.5 m below ground level. The soil was dark grey to black. It was air-dried, pulverised and passed through a 4.75 mm IS sieve before use. The soil classifies as inorganic clay of high compressibility (CH) under IS:1498 [13]. Its properties, determined in accordance with the relevant parts of IS:2720 [14], are given in Table 1. The DFS of 90% is well above the 50% threshold for very high expansiveness, and the soaked CBR of 1.41% makes the soil unsuitable as a pavement subgrade without treatment.

Table 1: Index and engineering properties of the untreated expansive soil

S.No	Property	Value	Standard
1	Differential free swell (%)	90	IS:2720 Part 40
2	Specific gravity	2.32	IS:2720 Part 3
3	Liquid limit (%)	67.56	IS:2720 Part 5
4	Plastic limit (%)	27.89	IS:2720 Part 5

S.No	Property	Value	Standard
5	Plasticity index (%)	39.67	IS:2720 Part 5
6	Optimum moisture content, modified Proctor (%)	26.78	IS:2720 Part 8
7	Maximum dry density (g/cc)	1.58	IS:2720 Part 8
8	Soaked CBR (%)	1.41	IS:2720 Part 16
9	Cohesion, undrained triaxial (kPa)	94.56	IS:2720
10	Angle of internal friction (°)	2.6	IS:2720
11	USCS classification	CH	IS:1498

2.2 Copper slag

Copper slag is a by-product of copper smelting. It was obtained from National Enterprises, Faridabad, Haryana, and was supplied as a black, glassy, irregular granular material of 0.075–4.75 mm particle size. The slag has a high specific gravity (3.6) and is rich in iron oxide and silica (Table 2). Its low content of calcium and aluminium oxides indicates that it is essentially inert, so any benefit to the clay is expected to come from physical action (dilution, densification and frictional interlock) rather than from cementitious reaction.

Table 2: Physical and chemical properties of copper slag

Physical property	Value	Chemical constituent	Content (%)
Particle shape	Irregular	Iron oxide (Fe_2O_3)	42–48
Appearance	Black and glassy	Silica (SiO_2)	26–30
Specific gravity	3.6	Aluminium oxide (Al_2O_3)	1.0–3.0
Bulk density (g/cc)	2.08	Calcium oxide (CaO)	1.0–2.0
Moisture content (%)	< 1.0	Magnesium oxide (MgO)	0.8–1.5
Particle size (mm)	0.075–4.75		

2.3 Zycobond

Zycobond is a sub-micron acrylic copolymer emulsion in which the polymer particles are smaller than 90 nm. It is a milky-white, water-dispersible liquid with a pH of 5–6, stable to heat and ultraviolet radiation (Table 3). When mixed with soil, the polymer coats and binds particles, and the very large surface area provides a high number of contact points for flexible bonding. The manufacturer's stated benifits include improved strength, stability and impermeability of locally available soils.

Table 3: Physical properties and composition of Zycobond

Physical property	Value	Component	Concentration (%)
Colour	Milky white	Acrylic polymer	34–36

Physical property	Value	Component	Concentration (%)
Odour	None	Water	62–65
Solubility in water	Dispersible	Acetic acid	0.2–1.0
pH	5–6	Methanol	0.1–0.2

2.4 Gravel

Gravel for the cushion layer in the plate load tests was collected from the Surampalem area, air-dried, pulverised and sieved through 4.75 mm. It has a specific gravity of 2.65 and consists of 65% gravel, 25% sand and 10% silt and clay.

3. Experimental methodology

3.1 Laboratory testing programme

Tests were carried out on the untreated soil and on each treated mix in accordance with the relevant Indian Standards: specific gravity (IS:2720 Pt.3), grain size analysis (IS:2720 Pt.4), liquid limit and plastic limit (IS:2720 Pt.5), differential free swell (IS:2720 Pt.40), modified Proctor compaction (IS:2720 Pt.8), soaked CBR (IS:2720 Pt.16) and undrained triaxial shear. Plasticity index was calculated as LL − PL. Compaction used the modified Proctor effort (4.36 kg rammer, five layers, 56 blows per layer). CBR specimens were compacted at the optimum moisture content of the respective mix and soaked for four days under a 5 kg surcharge before penetration at 1.25 mm/min with a 50 mm plunger. Triaxial specimens were 38 mm in diameter and 76 mm high, and cohesion and friction angle were obtained from Mohr's circles at different confining pressures. Static plate load tests followed IS:1888 [15].

3.2 Mix design phases

The programme was organised in three phases, staged as in Sai Ram et al. [11] so that the optimum content of the granular additive was fixed before the binder dosage was varied. In Phase I the properties of the untreated soil were determined. In Phase II, copper slag was added at 6, 10, 14, 18 and 22% by weight of the expansive soil, and DFS, Atterberg limits, specific gravity, compaction characteristics, soaked CBR and triaxial parameters were measured to identify the optimum copper slag content. In Phase III, the optimum copper slag content (18%) was combined with Zycobond at 0.5, 1.0, 1.5 and 2.0% by weight, and the same tests were repeated. Copper slag was spread over the pulverised soil and mixed to a uniform, lump-free blend before the Zycobond was added and mixed thoroughly. Static plate load tests were then carried out on the untreated soil, the soil with 18% copper slag, and the soil with 18% copper slag and 1.5% Zycobond.

3.3 Static plate load test setup

Plate load tests were conducted in a circular steel model tank of 600 mm diameter and 500 mm height. Each foundation bed comprised a 300 mm thick subgrade of untreated or treated expansive soil, compacted at the optimum moisture content in 60 mm layers, overlaid by a 150 mm gravel cushion placed at the OMC and MDD of the gravel in 50 mm layers. The test was run to failure under incremental static loading, with settlement recorded at each increment, in accordance with IS:1888.

4. Results and discussion

4.1 Effect of copper slag content

Table 4 and Fig. 1 summarise the results for the untreated soil and for soil treated with 6–22% copper slag. Copper slag progressively reduced the swelling and plasticity of the soil. DFS fell from 90% to 75% at 18% CS and to 70% at 22%. The liquid limit decreased from 67.6% to 59.0% at 18% CS, while the plastic limit rose from 27.9% to 35.8%, so that the plasticity index dropped from 39.7% to 23.2%, a 41.5% reduction. The specific gravity of the blend increased from 2.32 to 2.61 because of the high specific gravity of the slag (3.6). These changes follow from the replacement of swell-active montmorillonitic clay by non-plastic, non-absorbent granular particles, which reduces the amount of water the soil mass can adsorb. This interpretation is inferred from the index properties; mineralogical or microstructural tests were not part of the programme.

Table 4: Properties of expansive soil blended with copper slag (CS)

Mix	DFS (%)	Gs	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (g/cc)	CBR (%)	c (kPa)	φ (°)
Untreated soil	90	2.32	67.6	27.9	39.7	26.78	1.58	1.41	94.56	2.6
+ 6% CS	90	2.54	65.1	30.1	35.0	24.39	1.59	2.21	90.20	2.9
+ 10% CS	86	2.56	63.7	32.1	31.5	20.68	1.68	3.14	86.70	3.5
+ 14% CS	81	2.59	61.2	34.4	26.8	18.14	1.71	4.04	82.32	4.1
+ 18% CS ★	75	2.61	59.0	35.8	23.2	17.63	1.74	4.66	78.40	4.4
+ 22% CS	70	2.63	57.4	37.0	20.3	15.17	1.69	3.89	76.50	4.2

★ Optimum copper slag content (maximum MDD and CBR). Gs = specific gravity; c and φ = cohesion and angle of internal friction from undrained triaxial tests.

Compaction behaviour followed the usual optimum-then-decline pattern. OMC decreased steadily from 26.78% to 15.17% as copper slag content rose, reflecting the low water demand of the glassy slag particles and the smaller proportion of clay. MDD increased from 1.58 to 1.74 g/cc at 18% CS, a gain of 10.1%, and then fell to 1.69 g/cc at 22% CS. Beyond the optimum there is too little clay to bind and fill the voids between the slag particles, so packing efficiency drops.

Soaked CBR followed the same trend. It rose from 1.41% to 4.66% at 18% CS (+230%) and fell to 3.89% at 22% CS. Because both MDD and CBR peak at 18% CS, this content was adopted as the optimum even though DFS and PI continued to improve at 22%. Triaxial results show that the strength gain comes from friction rather than cohesion. The angle of internal friction increased from 2.6° to 4.4° at 18% CS, whereas cohesion decreased from 94.56 to 78.4 kPa (−17.1%), as cohesive fines were replaced by frictional particles. The net effect on CBR is positive, but 4.66% at 18% CS mix is still below the 8% minimum subgrade CBR recommended in IRC:37-2018 [16]. Copper slag alone is therefore insufficient, which motivated the addition of a binding agent.

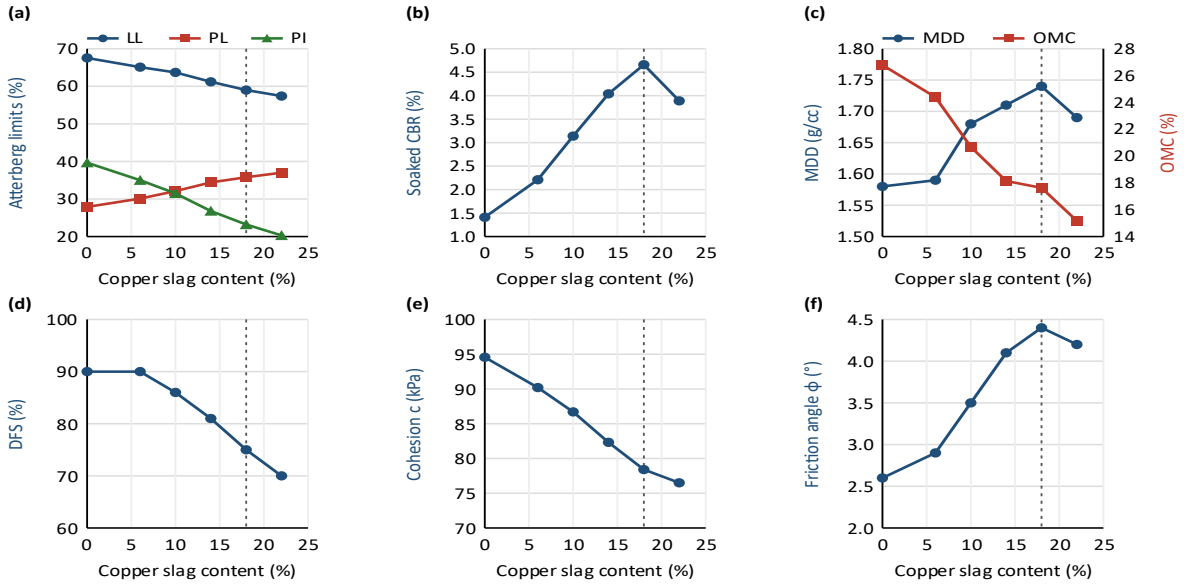


Fig. 1 Variation of properties of expansive soil with copper slag content: (a) Atterberg limit; (b) soaked CBR; (c) compaction parameters (MDD and OMC); (d) differential free swell; (e) cohesion; (f) angle of internal friction. The dotted line marks the optimum content (18%).

4.2 Effect of Zycobond content

Table 5 and Fig. 2 give the results for the 18% CS mix with 0.5–2.0% Zycobond. Zycobond reduced swelling and plasticity at every dosage. DFS dropped from 75% to 48% at 1.5% and to 39% at 2.0%. Using the classification of free swell index in which values above 50% are 'very high' and 35–50% are 'high', the 1.5% mix moves from the very high class to the high class. The liquid limit decreased from 59.0% to 51.8%, the plastic limit rose from 35.8% to 39.1%, and the plasticity index fell from 23.2% to 12.7% at 1.5% Zycobond (−68.0% relative to the untreated soil). At 2.0% the PI was 8.4%. The polymer is thought to coat and bind clay particles into larger aggregates, which reduces the surface available for water adsorption. The small rise in specific gravity (2.61 to 2.69) is consistent with such agglomeration, but was not investigated further.

Table 5: Properties of expansive soil with 18% copper slag blended with Zycobond (Z)

Mix	DFS (%)	Gs	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (g/cc)	CBR (%)	c (kPa)	φ (°)
18% CS + 0% Z	75	2.61	59.0	35.8	23.2	17.63	1.74	4.66	78.40	4.4
18% CS + 0.5% Z	67	2.63	57.3	36.7	20.5	17.00	1.77	5.78	75.00	4.7
18% CS + 1.0% Z	59	2.66	54.4	38.4	16.0	16.06	1.82	6.94	71.00	4.9
18% CS + 1.5% Z ★	48	2.68	51.8	39.1	12.7	15.18	1.87	8.11	67.00	5.3
18% CS + 2.0% Z	39	2.69	48.6	40.1	8.4	14.76	1.81	7.26	58.00	5.7

★ Optimum Zycobond dosage (maximum MDD and CBR).

OMC decreased continuously, from 17.63% to 14.76%, as Zycobond content increased. MDD increased from 1.74 to 1.87 g/cc at 1.5% Zycobond and then declined to 1.81 g/cc at 2.0%. Soaked CBR increased from 4.66% to 5.78%, 6.94% and 8.11% for 0.5%, 1.0% and 1.5% Zycobond, a 74% gain over the 18% CS mix, and then decreased to 7.26% at 2.0%. The reduction beyond 1.5% suggests that polymer in excess of the amount needed to

coat the particle surfaces no longer contributes to bonding and may weaken inter-particle contact. This explanation was not tested directly. On this basis 1.5% was taken as the optimum Zycobond dosage.

Cohesion decreased and friction angle increased with Zycobond content. Cohesion fell from 78.4 to 67 kPa and friction angle rose from 4.4° to 5.3° at 1.5% Zycobond. The optimum mix (soil + 18% CS + 1.5% Zycobond) reaches a soaked CBR of 8.11%, which is marginally above the 8% subgrade minimum in IRC:37-2018 [16]. The margin is only 0.11 percentage points, so the result should be treated as meeting, rather than comfortably exceeding, the requirement. The value is comparable to the soaked CBR of 8.07% reported by Sai Ram et al. [11] for a marine clay stabilised with 10% foundry sand and 1.5% alkali-activated geopolymer, although the soils, additives and binding mechanisms differ.

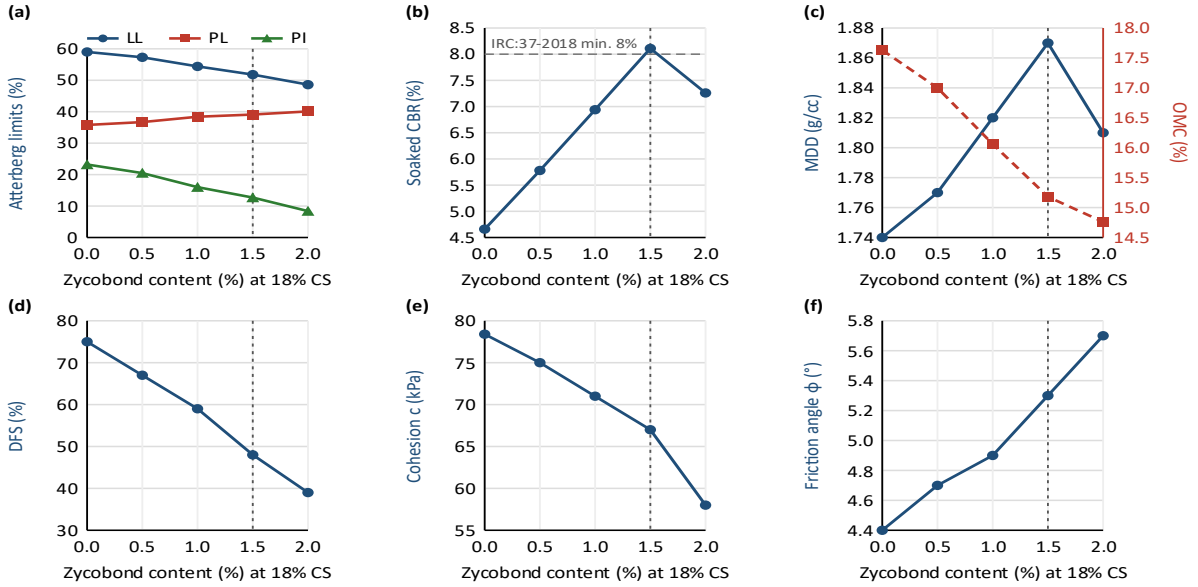


Fig. 2 Variation of the properties of expansive soil with 18% copper slag with Zycobond content: a Atterberg limit; b soaked CBR; c compaction parameters (MDD and OMC); d differential free swell; e cohesion; f angle of internal friction. The dotted line marks the optimum dosage (1.5%).

4.3 Regression analysis

Linear and quadratic least-squares models were fitted to the dosage–response data to give explicit design equations. Table 6 lists the linear equations with their coefficients of determination and p-values, together with the R^2 of the quadratic model. In the copper slag series x is the CS content (%, 0–22%), and in the Zycobond series y is the Zycobond content (%, 0–2%) at 18% CS.

Table 6: Regression models for the effect of copper slag (x) and Zycobond (y) on soil properties

Series	Response	Linear model	R^2 (linear)	p	R^2 (quadratic)
Copper slag	DFS (%)	−0.977x + 93.40	0.914	0.0029	0.988
Copper slag	PI (%)	−0.911x + 40.03	0.996	< 0.0001	0.996
Copper slag	OMC (%)	−0.539x + 26.76	0.971	0.0003	0.975
Copper slag	MDD (g/cc)	0.0069x + 1.585	0.720	0.033	0.807
Copper slag	CBR (%)	0.139x + 1.604	0.833	0.011	0.907

Series	Response	Linear model	R^2 (linear)	p	R^2 (quadratic)
Zycobond	DFS (%)	−18.20y + 75.80	0.996	0.0001	0.998
Zycobond	PI (%)	−7.48y + 23.64	0.995	0.0002	0.997
Zycobond	OMC (%)	−1.512y + 17.64	0.987	0.0006	0.990
Zycobond	MDD (g/cc)	0.048y + 1.754	0.583	0.133	0.817
Zycobond	CBR (%)	1.506y + 5.044	0.782	0.047	0.934

n = 6 data points for the copper slag series and n = 5 for the Zycobond series.

DFS, PI and OMC are close to linear in both dosages (R^2 = 0.914–0.996), which is consistent with a dilution and binding mechanism in which each increment of additive removes a roughly constant amount of swell-active clay or free water. In contrast, MDD and CBR rise and then fall, so linear models fit them poorly (R^2 = 0.58–0.83). Quadratic models improve the fit (Fig. 3), raising R^2 for CBR from 0.833 to 0.907 in the copper slag series and from 0.782 to 0.934 in the Zycobond series. The quadratic equations for CBR are $CBR = -0.0062x^2 + 0.2754x + 1.186$ for copper slag and $CBR = -1.123y^2 + 3.752y + 4.483$ for Zycobond. The corresponding MDD equations are $MDD = -0.00036x^2 + 0.0148x + 1.560$ and $MDD = -0.0514y^2 + 0.1509y + 1.728$.

The vertex of the fitted Zycobond CBR parabola lies at 1.67%, close to the experimentally observed optimum of 1.5%. The copper slag parabola peaks at about 22.3%, which is higher than the measured optimum of 18%, because the measured response rises almost linearly to 18% and then drops sharply at 22%, a shape a single parabola cannot reproduce. The experimental optimum rather than the fitted vertex was therefore used. These models are based on only five or six points, have few residual degrees of freedom, and were not tested against independent data. They are suitable for interpolation within the tested dosage ranges only and should not be extrapolated.

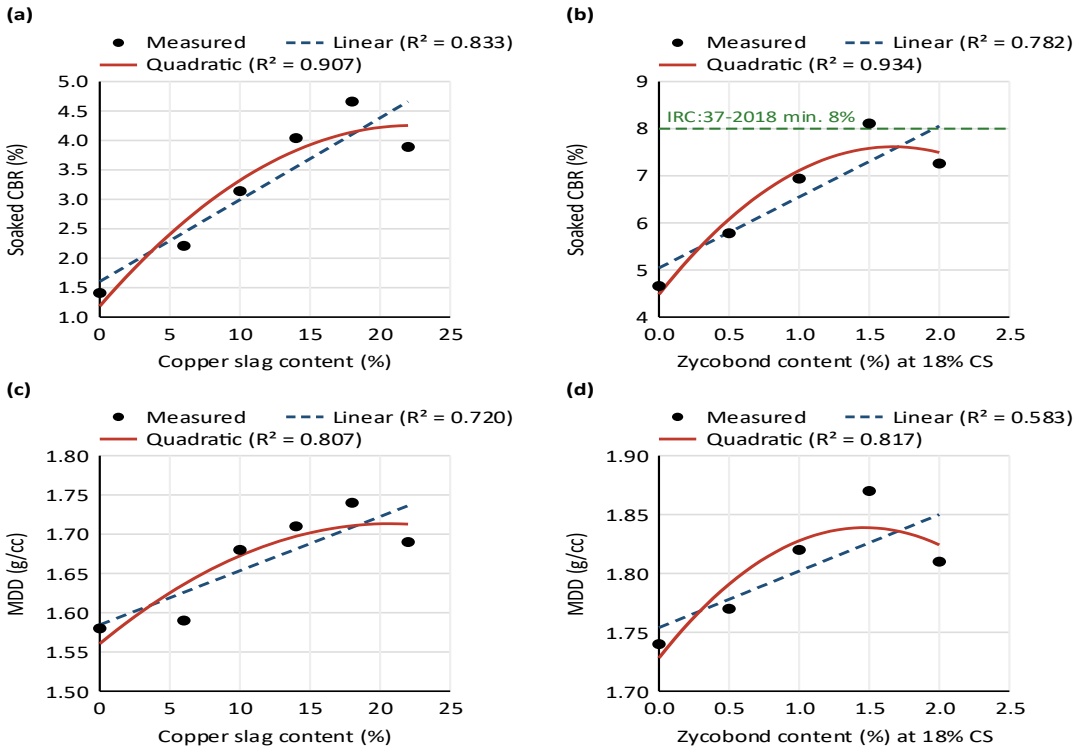


Fig. 3 Linear and quadratic regression models: a soaked CBR against copper slag content; b soaked CBR against Zycobond content (18% CS); c MDD against copper slag content; d MDD against Zycobond content (18% CS).

4.4 Static plate load test

Table 7 and Fig. 4 show that both treatments stiffened the model foundation bed and increased its capacity. The untreated expansive soil bed failed at 720 kPa with a settlement of 3.12 mm. With 18% copper slag the ultimate pressure rose to 1100 kPa (+52.8%) and the settlement at failure was 2.35 mm. With 18% copper slag and 1.5% Zycobond the bed carried 1460 kPa (+102.8%) with a settlement of 1.78 mm, which is 42.9% lower than the untreated bed even though the load was twice as high. At any given pressure the treated beds settled less than the untreated bed, indicating a stiffer foundation response that results from the higher density, greater frictional resistance and lower swell potential of the treated subgrade.

Table 7: Static plate load test results for model foundation beds with a 150 mm gravel cushion

S.No	Subgrade (300 mm)	Ultimate load (kPa)	Settlement at failure (mm)	Load increase over untreated (%)
1	Untreated expansive soil	720	3.12	Baseline
2	Expansive soil + 18% CS	1100	2.35	+52.8
3	Expansive soil + 18% CS + 1.5% Z	1460	1.78	+102.8

The tests were small-scale laboratory model tests in a 600 mm diameter tank; scale and boundary effects mean the values indicate relative improvement and are not field bearing capacities.

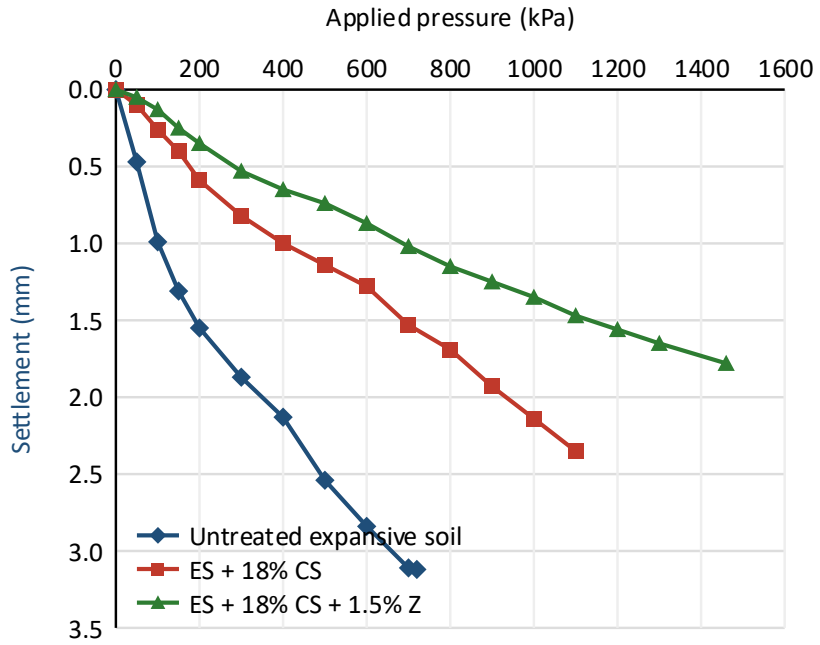


Fig. 4 Pressure–settlement curves from static plate load tests on model foundation beds: untreated expansive soil (ES), ES + 18% copper slag (CS), and ES + 18% CS + 1.5% Zycobond (Z). Curves were reconstructed from the recorded test plots and end at the ultimate loads in Table 7.

4.5 Comprehensive performance summary

Table 8 and Fig. 5 compare all measured properties for the untreated soil, the soil with the optimum copper slag content, and the soil with the optimum combination. The two additives act in a complementary way. Copper slag supplies the bulk of the density gain and reduces cohesion, plasticity and swell by dilution, whereas Zycobond further reduces swell and plasticity and adds the increment of CBR that takes the mix above the subgrade requirement.

Table 8: Comparison of untreated, copper slag-treated and copper slag + Zycobond-treated expansive soil

Property	**Untreated**	**+ 18% CS**	**+ 18% CS + 1.5% Z**	**Change (untreated to optimum)**
Differential free swell (%)	90	75	48	−46.7%
Specific gravity	2.32	2.61	2.68	+15.5%
Liquid limit (%)	67.6	59.0	51.8	−23.3%
Plastic limit (%)	27.9	35.8	39.1	+40.2%
Plasticity index (%)	39.7	23.2	12.7	−68.0%
OMC (%)	26.78	17.63	15.18	−43.3%
MDD (g/cc)	1.58	1.74	1.87	+18.4%
Soaked CBR (%)	1.41	4.66	8.11	+475%
Cohesion (kPa)	94.56	78.40	67.00	−29.1%
Friction angle (°)	2.6	4.4	5.3	+104%
Ultimate plate load (kPa)	720	1100	1460	+102.8%
Settlement at failure (mm)	3.12	2.35	1.78	−42.9%

Percentage changes are calculated relative to the untreated soil.

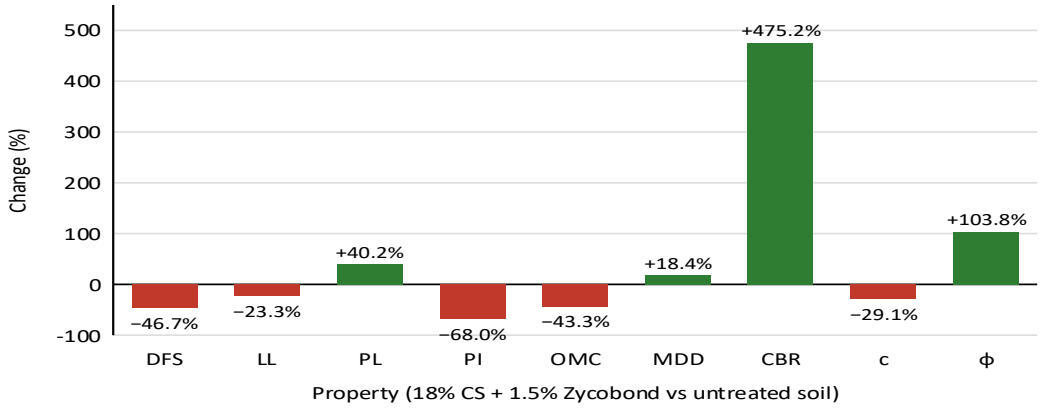


Fig. 5 Percentage change in measured properties from untreated expansive soil to the optimum mix (18% CS + 1.5% Zycobond). Decreases in DFS, LL, PI, OMC and cohesion and increases in PL, MDD, CBR and friction angle are shown.

5. Conclusions

1. The untreated Ramachandrapuram expansive soil is a very high-swell, high-plasticity clay (CH): LL = 67.6%, PI = 39.7%, DFS = 90% and soaked CBR = 1.41%. It is unsuitable as a pavement subgrade without treatment.
2. The optimum copper slag content is 18% by weight. At this content DFS fell to 75%, PI by 41.5% to 23.2%, OMC by 34.2% to 17.63%, MDD rose by 10.1% to 1.74 g/cc, and soaked CBR rose by 230% to 4.66%. Above 18% both MDD and CBR declined. Copper slag improved strength through densification and friction (φ from 2.6° to 4.4°) while reducing cohesion by 17.1%, and was not sufficient by itself to reach the 8% subgrade CBR.
3. The optimum Zycobond dosage for the 18% copper slag mix is 1.5%. The combined mix reduced DFS by 46.7% to 48%, LL by 23.3% to 51.8%, PI by 68.0% to 12.7%, and OMC by 43.3% to 15.18%, while MDD increased by 18.4% to 1.87 g/cc. Soaked CBR rose from 1.41% to 8.11% (+475%), marginally above the 8% minimum subgrade CBR in IRC:37-2018. At 2.0% Zycobond, MDD and CBR declined.
4. DFS, PI and OMC varied almost linearly with additive dosage (R^2 = 0.914–0.996), whereas MDD and CBR followed optimum-then-decline curves that are better described by quadratic models (CBR R^2 = 0.907 for copper slag and 0.934 for Zycobond). The regression equations are valid for interpolation within the tested dosage ranges.
5. Static plate load tests on model foundation beds showed that ultimate bearing pressure increased from 720 kPa (untreated) to 1100 kPa (18% CS) and 1460 kPa (18% CS + 1.5% Zycobond), an increase of 102.8%, while settlement at failure decreased from 3.12 mm to 1.78 mm.
6. Combined treatment with 18% copper slag and 1.5% Zycobond is a technically effective way of improving expansive soil subgrades, and it puts a copper smelting by-product to productive use. Field trials and durability assessment are needed before the treatment is specified in practice.

6. Limitations and future work

Mechanisms: The mechanisms proposed for the effects of copper slag and Zycobond are inferred from index, compaction and strength results. X-ray diffraction, scanning electron microscopy and zeta-potential or chemical analyses were not carried out, and should be added to confirm how the polymer interacts with the clay. Sai Ram et al. [11] used X-ray diffraction in this way to confirm the mineralogical changes in foundry sand–geopolymer treated clay.

Curing and durability: Results do not include a systematic study of curing time, wet–dry cycling, long-term swell pressure or leaching of heavy metals from the slag. Copper slag contains metal oxides, and environmental leaching tests are needed before use.

Optimum margin: The optimum mix exceeds the 8% CBR threshold by a narrow margin. Replicate testing and, where relevant, a more conservative design CBR should be considered.

Model tests: The plate load tests were small-scale laboratory tests on a single soil. Cyclic plate load tests on model flexible pavements, pavement thickness design to IRC:37-2018, cost analysis and field trials are recommended.

Other additives: The combination of copper slag and Zycobond with fibres or small amounts of cement or lime was not examined and could be explored to increase strength further.

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