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Stabilization of marine clay subgrade with ferrochrome slag and calcium oxide: laboratory characterisation and Data-driven Prediction

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Abstract

Marine clay subgrades are highly plastic, swell on wetting and have a low California bearing ratio (CBR), which makes them unsuitable for flexible pavements without improvement. This study examines the stabilisation of a high-plasticity marine clay (CH) from Kakinada, India, with ferrochrome slag (FCS), an industrial by-product, and calcium oxide (CaO). The clay was treated with 5–20% FCS to find the optimum slag content, and 1.0–2.5% CaO was then added to the optimum FCS mix. Differential free swell, Atterberg limits, modified Proctor compaction and CBR tests were carried out on nine mixes. The optimum contents were 15% FCS and 2.0% CaO. At 15% FCS, the plasticity index fell from 38.3% to 18.9%, the differential free swell from 80% to 52%, and the CBR rose from 1.13% to 6.10%. With 2.0% CaO added, the plasticity index fell to 12.0%, the differential free swell to 26% and the optimum moisture content from 33.02% to 10.23%, while the maximum dry density rose from 1.378 to 1.932 g/cm³ and the CBR reached 8.24%, which exceeds the 8% target adopted from IRC:37-2012 for capping layers. Linear and second-degree polynomial regression equations were fitted to relate the additive contents to the measured responses, and machine learning and Bayesian regression models were developed from the measured data for use within the tested range. FCS with a small dose of CaO is therefore a technically effective means of stabilising marine clay subgrades while reusing an industrial waste, although the findings are limited to one remoulded clay, and durability and chromium leaching remain to be evaluated.

Keywords: marine clay; ferrochrome slag; calcium oxide; soil stabilization; flexible pavement subgrade; CBR; Atterberg limits; regression analysis

1. Introduction

Marine clays are soft, fine-grained sediments deposited in saline water and are found along much of the Indian coastline, including Andhra Pradesh, Tamil Nadu, Kerala, Odisha and West Bengal. Deposition in electrolyte-rich water promotes flocculation and an open, card-house fabric with a high void ratio [1]. The resulting soil is highly compressible, has low shear strength, and is sensitive to changes in moisture content and pore-fluid chemistry [1,2]. Marine clay from the Kakinada coast, for example, has been reported to have high plasticity, a swell pressure of 160 kN/m² and a very slow consolidation rate, with about 311.6 days required for 90% consolidation [2].

The strength of the subgrade governs the thickness, cost and service life of a flexible pavement [3]. Variability in subgrade properties forces conservative designs, which leads either to thicker and more expensive pavements or to poor performance and high maintenance costs. Marine clay subgrades are associated with rutting, longitudinal cracking and localised surface failure, because seasonal changes in moisture content cause volume change and repeated wheel loads cause progressive deformation. Remedies such as soil replacement, sand cushions, stone

columns, band drains and reinforcement can be effective for foundations, but they are generally costly or impractical along long pavement alignments, and re-routing a road to avoid the deposit is rarely possible.

Chemical stabilisation is therefore the most widely adopted option for pavement subgrades. Lime reduces the plasticity and swelling potential of fine-grained soils and increases their strength through cation exchange, flocculation and pozzolanic reactions [4]. A considerable body of work has applied lime, alone or together with other materials, to marine clays: lime with Recron-3s fibre [5], sawdust with lime [6,7], cockle shell powder [8], Jarofix with polypropylene fibre [9], and a copper slag cushion over lime-stabilised clay [10]. Granulated or ground granulated blast furnace slag (GGBS), alone or combined with lime, has also been examined for soft soils generally [11–14]. These studies show that industrial by-products can be used to improve weak soils, which is attractive because disposal of industrial waste is itself an environmental problem.

Ferrochrome slag (FCS) is one such by-product. It is generated in electric-arc furnaces during the production of ferrochrome, an essential alloy for stainless steel, at a rate of about 1.1–1.6 t of slag per tonne of ferrochrome [25]. Only a small proportion of the slag is put to useful applications, and most of it is disposed of at site. FCS has a rough, porous surface, good adhesion and abrasion characteristics, and contains no clay or organic matter, although its water absorption is relatively high. Air-cooled ferrochromium slag has been reported to perform as well as or better than natural aggregate in the granular layers of flexible pavements [15]. In the literature reviewed for this study, however, FCS has been examined mainly as an aggregate, and only recently as an additive for soft clay, in a study combining FCS with cement in kaolin [26]. Its use with CaO in marine clay has not been documented. In a related study of marine clay from the Visakhapatnam–Chennai Industrial Corridor, foundry sand combined with an alkali-activated geopolymer raised the CBR from 1.34% to 8.07% [24]; the present work examines a different industrial by-product, FCS, together with a lime-type additive.

Beyond measuring the effect of each additive, a predictive framework is needed to quantify how the additives influence the geotechnical response of the clay and how reliably a design target is met. Artificial intelligence and machine learning (ML) are now used in many areas of geotechnical engineering to model non-linear soil behaviour from laboratory data [27], and ensemble and kernel-based methods such as random forests [28], gradient boosting [29], support vector regression [30] and Gaussian process regression [31] are commonly applied to stabilised soils. Where the data set is small, as in most laboratory programmes, simple polynomial response-surface models remain competitive [32], and Bayesian regression [33] expresses the uncertainty of a prediction as a probability rather than a single value, which is useful when a result must be compared with a design threshold such as a minimum CBR.

This paper addresses three gaps. First, FCS has not, in the literature reviewed, been combined with CaO for marine clay. Second, explicit regression equations and ML models that relate FCS and CaO content to the swelling, plasticity, compaction and CBR responses of this material are not available. Third, the reliability with which the treated clay meets the CBR target has not been expressed in probabilistic terms. The objectives were therefore (i) to determine the index and engineering properties of a marine clay from Kakinada; (ii) to establish the optimum FCS content (5–20%) for improving its swelling, plasticity, compaction and CBR characteristics; (iii) to establish the optimum CaO content (1.0–2.5%) when used as a chemical additive with the optimum FCS content; (iv) to develop regression and ML models for predicting the response of the clay to the two additives; and (v) to assess the probability that the treated clay meets the 8% CBR target using Bayesian regression.

2. Materials

2.1 Marine clay

The marine clay was collected from a depth of 0.3–0.6 m at Kakinada Sea Ports Limited, Kakinada, Andhra Pradesh, India. It was air-dried, pulverised and passed through a 4.75 mm IS sieve before use. The clay is black, fine-grained and highly plastic, has a medium dry strength and gives off an odour of decaying vegetation. It is

classified as high-plasticity clay (CH) according to IS 1498 [23]. Its grain-size distribution and engineering properties are given in Table 1.

Table 1. Grain-size distribution and engineering properties of the untreated marine clay

Property	Value
Gravel (%)	0
Sand (%)	11.0
Silt (%)	43.0
Clay (%)	46.0
Specific gravity	2.44
Differential free swell (%)	80
Liquid limit (%)	69.60
Plastic limit (%)	31.30
Plasticity index (%)	38.30
Classification (IS 1498)	CH
Maximum dry density (g/cm³)	1.378
Optimum moisture content (%)	33.02
CBR (%)	1.13

2.2 Ferrochrome slag

The ferrochrome slag (FCS) was obtained as a by-product of ferrochrome production, which takes place in electric-arc furnaces at 1500–1700 °C with coke as the reducing agent. The slag is dark to light grey, insoluble in water and consists mainly of SiO_2, Al_2O_3 and MgO, with 15% Cr_2O_3 (Table 2). It has a specific gravity of 3.48, contains 67% coarse and 33% fine particles, and has a maximum dry density of 2.32 g/cm³ at an optimum moisture content of 7% (Table 3).

Table 2. Chemical composition of the ferrochrome slag

Constituent	Content (% by weight)
SiO_2	30
Al_2O_3	26
MgO	23
Cr_2O_3	15
FeO	4
CaO	2

Table 3. Physical properties of the ferrochrome slag

Property	Value
Coarse fraction (%)	67
Fines (%)	33
Specific gravity	3.48
Optimum moisture content (%)	7
Maximum dry density (g/cm³)	2.32
Soaked CBR (%)	6.39
Colour	Dark to light grey
Solubility in water	Insoluble

2.3 Calcium oxide

Calcium oxide (CaO, quicklime) was used as the chemical additive.

3. Experimental methodology

3.1 Mix proportions and specimen preparation

The study was carried out in five phases: (I) characterisation of the untreated marine clay; (II) characterisation of the FCS; (III) determination of the optimum FCS content by treating the clay with 5, 10, 15 and 20% FCS; (IV) determination of the optimum CaO content by adding CaO to the clay treated with the optimum FCS content; and (V) regression, machine learning and Bayesian analysis of the measured results. The nine mixes tested are listed in Table 4. FCS contents are expressed as a percentage of the dry weight of the mixture and CaO contents as a percentage of dry weight. For each mix, the dry marine clay and FCS were mixed thoroughly, CaO was spread over the pulverised mixture and blended until uniform and free of lumps, and water was then added at the required moisture content.

Table 4. Mix designations and compositions

Mix	Composition (percentages by dry weight)
MC	Marine clay (untreated)
F5	95% marine clay + 5% FCS
F10	90% marine clay + 10% FCS
F15	85% marine clay + 15% FCS
F20	80% marine clay + 20% FCS
F15C1.0	F15 + 1.0% CaO
F15C1.5	F15 + 1.5% CaO
F15C2.0	F15 + 2.0% CaO
F15C2.5	F15 + 2.5% CaO

3.2 Laboratory tests

All tests were performed in accordance with the relevant parts of IS 2720. Water content was determined by oven drying at 110 ± 5 °C for 24 h [16] as $w = (M_2 - M_3)/(M_3 - M_1) \times 100$, where M_1 is the mass of the container with lid, M_2 the mass of the container, lid and wet soil, and M_3 the mass of the container, lid and dry soil. Specific gravity was determined with a density bottle using $G = (M_2 - M_1)/[(M_2 - M_1) - (M_3 - M_4)]$ [17], where M_1 is the mass of the empty bottle, M_2 the mass of bottle and dry soil, M_3 the mass of bottle, soil and water, and M_4 the mass of the bottle filled with water. Grain-size distribution was obtained by sieve analysis [18,23]. The liquid limit and plastic limit were determined on the soil–admixture mixes [19], and the plasticity index was calculated as their difference.

Differential free swell (DFS) was measured as the increase in volume of an oven-dried specimen submerged in distilled water relative to its volume in kerosene [21], $DFS = (Vd - Vk)/Vk \times 100$, where Vd and Vk are the specimen volumes read from graduated cylinders containing distilled water and kerosene, respectively. Compaction characteristics (optimum moisture content, OMC, and maximum dry density, MDD) were determined with the modified Proctor test [20]. The CBR was determined from the loads at 2.5 mm and 5.0 mm penetration of the load–penetration curve, and if the CBR at 5.0 mm exceeded that at 2.5 mm, the test was repeated and the higher value was adopted [22]. IRC:37-2012 requires a minimum design CBR of 5% for the subgrade and 8% for a capping layer [3]; an 8% CBR was adopted here as the target for the treated clay.

3.3 Data-driven analysis

The measured results were analysed with regression, machine learning (ML) and Bayesian methods. The data set comprised the nine mixes of Table 4, namely the untreated clay, four FCS mixes (5–20%) and four FCS–CaO mixes (15% FCS with 1.0–2.5% CaO), with FCS content and CaO content as the two input variables and CBR, plasticity index (PI), differential free swell (DFS), OMC and MDD as the responses. Only the measured values were used. No synthetic or augmented data were generated, so every model described below is trained on nine

observations and is intended for interpolation within the tested range of FCS and CaO contents, not for extrapolation beyond it. All calculations were carried out in Python using scikit-learn [32].

Regression. For each additive, the response was fitted against content by least-squares linear regression and by second-degree polynomial regression, using the five mixes of each series (the untreated clay and four FCS mixes for FCS; the 15% FCS mix and four FCS–CaO mixes for CaO). The coefficient of determination (R^2) and the p-value of the slope were calculated for the linear models, and the position of the maximum of each fitted parabola was compared with the measured optimum.

Machine learning. Six models were compared for predicting CBR, PI and DFS from FCS and CaO content: multiple linear regression, ridge-regularised second-degree polynomial regression, random forest (RF) [28] with 500 trees and a maximum depth of 3, gradient boosting (GB) [29] with 200 estimators, a learning rate of 0.05 and a maximum depth of 2, support vector regression (SVR) [30] with a radial basis function kernel and C = 10, and Gaussian process regression (GPR) [31] with a radial basis function kernel plus a white-noise term. Because the data set is small, performance was assessed by leave-one-out cross-validation (LOOCV), in which each mix in turn is withheld, the model is fitted to the other eight, and the withheld mix is predicted. The cross-validated R^2, root-mean-square error (RMSE) and mean absolute error (MAE) were calculated from the nine withheld predictions. The relative influence of the two additives was assessed from the permutation importance of the RF model.

Bayesian regression. The CBR was modelled by Bayesian linear regression on the second-degree terms of FCS and CaO content, with a non-informative prior [33]. The posterior predictive distribution of the CBR of a mix is then a Student-t distribution with mean μ and scale s, and the probability that the CBR of that mix reaches a threshold c is $P(CBR \geq c) = 1 - F_t[(c - \mu)/s]$, where F_t is the cumulative distribution function of the t distribution with the residual degrees of freedom. Probabilities were calculated for the 5% minimum subgrade CBR and the 8% target CBR.

4. Results and discussion

4.1 Effect of FCS on swelling and plasticity

Adding FCS progressively reduced the swelling and plasticity of the marine clay (Table 5, Fig. 1a,d). The differential free swell fell from 80% for the untreated clay to 72%, 63%, 52% and 42% at 5, 10, 15 and 20% FCS, a reduction of 47.5% at the highest dosage. The liquid limit decreased from 69.6% to 52.1% (a drop of 17.5 percentage points), while the plastic limit rose from 31.3% to 39.8%. Because the two limits moved in opposite directions, the plasticity index declined steeply, from 38.3% to 31.1%, 25.0%, 18.9% and 12.3%, which corresponds to reductions of 18.8%, 34.7%, 50.7% and 67.9%, respectively. At 15% FCS the liquid limit (56.3%) is still above 50%, so the mixture remains in the high-plasticity range, although its plasticity index is halved.

Table 5. Differential free swell and Atterberg limits of the marine clay treated with FCS

Mix	FCS (%)	DFS (%)	LL (%)	PL (%)	PI (%)
MC	0	80	69.60	31.30	38.30
F5	5	72	64.50	33.40	31.10
F10	10	63	60.20	35.20	25.00
F15	15	52	56.30	37.40	18.90
F20	20	42	52.10	39.80	12.30

FCS is a non-plastic, granular material with a specific gravity of 3.48. Replacing part of the clay with FCS dilutes the fraction of active clay minerals responsible for water adsorption and swelling, and the slag particles act as an inert skeleton within the clay matrix. This is consistent with the reduction in free swell and with the shift in the plasticity limits.

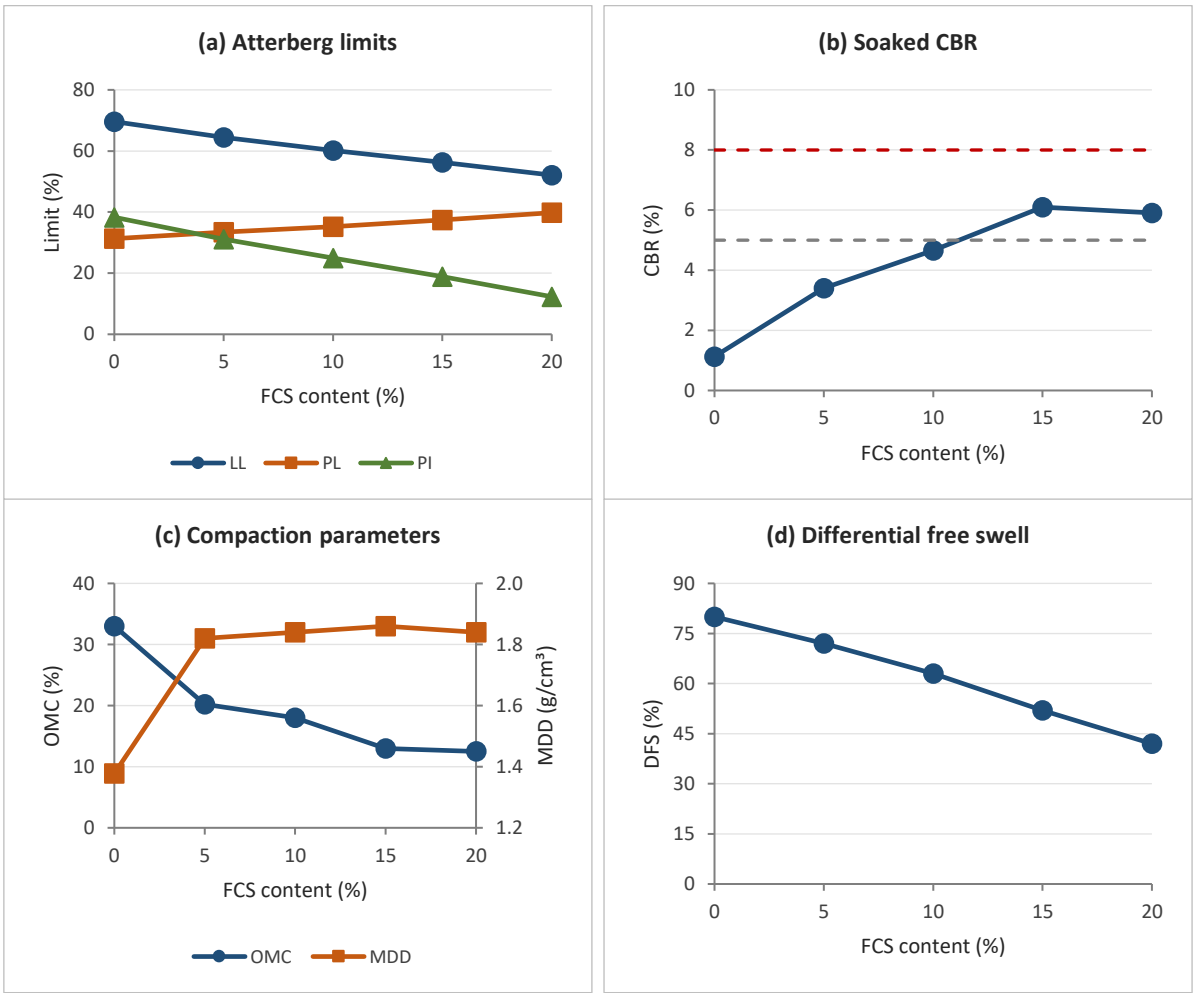


Figure 1. Variation of the properties of the marine clay with FCS content: (a) Atterberg limits; (b) soaked CBR (dashed lines mark the 5% and 8% CBR levels); (c) compaction parameters; (d) differential free swell (DFS)

4.2 Effect of FCS on compaction and CBR

FCS had a strong effect on the compaction characteristics (Table 6, Fig. 1c). The OMC fell from 33.02% for the untreated clay to 20.20% at 5% FCS and to 12.50% at 20% FCS, while the MDD increased from 1.378 g/cm³ to 1.820 g/cm³ at 5% FCS (an increase of 32.1%). The MDD reached a maximum of 1.860 g/cm³ at 15% FCS (an increase of 35.0%) and declined slightly to 1.840 g/cm³ at 20%. The large reduction in OMC reflects the low water demand of the slag (OMC of 7%) and the reduced water-holding capacity of the clay–slag matrix, and the increase in MDD reflects the much higher specific gravity of the slag.

The CBR increased from 1.13% for the untreated clay to 3.40%, 4.66% and 6.10% at 5, 10 and 15% FCS, an increase of 439.8% at 15% FCS, and then decreased marginally to 5.91% at 20% FCS (Fig. 1b). The peak of CBR and MDD at 15% indicates that, beyond this dosage, there is too little clay to bind the coarser slag particles, so the additional slag contributes little further interlock; the mix at 15% FCS was therefore taken as the optimum. At 6.10% its CBR exceeds the 5% minimum subgrade CBR of IRC:37-2012 [3] but remains below the 8% target adopted in this study, which motivated the addition of CaO.

Table 6. Compaction characteristics and CBR of the marine clay treated with FCS

Mix	FCS (%)	OMC (%)	MDD (g/cm³)	CBR (%)	CBR increase over MC (%)
MC	0	33.02	1.378	1.13	–
F5	5	20.20	1.820	3.40	200.9
F10	10	18.00	1.840	4.66	312.4
F15	15	13.00	1.860	6.10	439.8
F20	20	12.50	1.840	5.91	423.0

4.3 Effect of CaO on the FCS-treated clay

CaO was added to the clay treated with the optimum 15% FCS at 1.0, 1.5, 2.0 and 2.5% (Tables 7 and 8, Fig. 2). The differential free swell decreased from 52% to 49%, 37%, 26% and 14%, and the plasticity index from 18.90% to 16.99%, 14.54%, 12.00% and 10.88%. This reduction came mainly from an increase in plastic limit (37.40% to 43.35%), since the liquid limit changed only slightly (56.30% to 54.23%). Both swell and plasticity were still decreasing at 2.5% CaO.

Table 7. Differential free swell and Atterberg limits of the marine clay treated with 15% FCS and CaO

Mix	CaO (%)	DFS (%)	LL (%)	PL (%)	PI (%)
F15	0	52	56.30	37.40	18.90
F15C1.0	1.0	49	56.06	39.07	16.99
F15C1.5	1.5	37	55.49	40.95	14.54
F15C2.0	2.0	26	54.29	42.29	12.00
F15C2.5	2.5	14	54.23	43.35	10.88

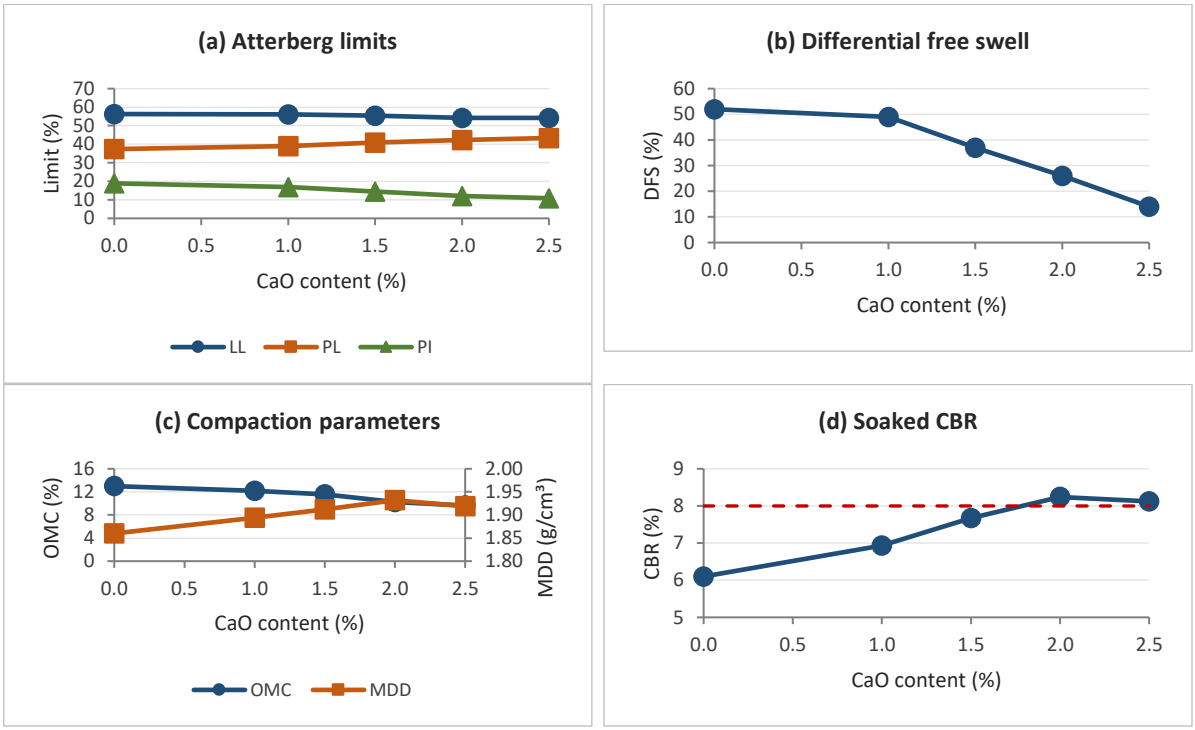


Figure 2. Variation of the properties of the marine clay treated with 15% FCS with CaO content: (a) Atterberg limits; (b) differential free swell (DFS); (c) compaction parameters; (d) soaked CBR (dashed line marks the 8% target; 0% CaO is the 15% FCS mix)

The compaction and strength parameters, in contrast, passed through an optimum (Table 8). The OMC decreased steadily from 13.00% to 9.64%, but the MDD increased from 1.860 g/cm³ to a maximum of 1.932 g/cm³ at 2.0% CaO and then fell to 1.919 g/cm³ at 2.5%. The CBR followed the same pattern, rising from 6.10% to 6.93%, 7.67% and 8.24% at 1.0, 1.5 and 2.0% CaO, and falling slightly to 8.12% at 2.5% (Fig. 2d). The addition of 2.0% CaO was therefore taken as optimum: it gives the highest MDD and CBR, and the further reductions in swell and plasticity at 2.5% are small compared with the loss in strength and density. At 8.24% the CBR of the F15C2.0 mix exceeds the 8% target, which is also the capping-layer minimum in IRC:37-2012 [3].

Table 8. Compaction characteristics and CBR of the marine clay treated with 15% FCS and CaO

Mix	CaO (%)	OMC (%)	MDD (g/cm³)	CBR (%)
F15	0	13.00	1.860	6.10
F15C1.0	1.0	12.18	1.894	6.93
F15C1.5	1.5	11.57	1.912	7.67
F15C2.0	2.0	10.23	1.932	8.24
F15C2.5	2.5	9.64	1.919	8.12

The compaction response differs from that usually reported for lime-treated marine clay, where the MDD decreases and the OMC increases as lime is added [5]. Here the matrix is dominated by dense, low-water-demand slag, and the small CaO addition acts mainly on the clay fraction, which explains why density and OMC continue to improve. The combined effect of the two additives relative to the untreated clay is summarised in Table 9.

Table 9. Summary of the laboratory test results for the untreated and treated marine clay

Property	MC	F15	F15C2.0	Change, F15 (%)	Change, F15C2.0 (%)
Specific gravity	2.44	2.63	2.71	+7.8	+11.1
Differential free swell (%)	80	52	26	−35.0	−67.5
Liquid limit (%)	69.60	56.30	54.29	−19.1	−22.0
Plastic limit (%)	31.30	37.40	42.29	+19.5	+35.1
Plasticity index (%)	38.30	18.90	12.00	−50.7	−68.7
OMC (%)	33.02	13.00	10.23	−60.6	−69.0
MDD (g/cm³)	1.378	1.860	1.932	+35.0	+40.2
CBR (%)	1.13	6.10	8.24	+439.8	+629.2

4.4 Regression analysis

Table 10 gives the linear regression equations for the effect of each additive on the five measured responses, together with the coefficient of determination (R^2) and the p-value of each linear fit and the R^2 of the corresponding second-degree polynomial. In the equations x is the additive content in per cent. Each series contains five mixes, so the p-values and R^2 values describe how well a straight line or parabola summarises the measured trend, and the polynomial fits, which have three parameters for five points, should not be read as evidence of an underlying quadratic law.

Table 10. Linear regression equations for the effect of FCS (0–20%) and of CaO (0–2.5%, on 15% FCS) on the measured responses

Additive	Response	Linear equation	R^2	p	R^2 (quadratic)
FCS	CBR (%)	0.2452x + 1.788	0.895	0.0150	0.990
FCS	PI (%)	−1.284x + 37.96	0.999	<0.001	0.999
FCS	DFS (%)	−1.920x + 81.00	0.997	<0.001	0.999

Additive	Response	Linear equation	R^2	p	R^2 (quadratic)
FCS	OMC (%)	−0.9648x + 28.99	0.841	0.0283	0.964
FCS	MDD (g/cm³)	0.0193x + 1.555	0.542	0.156	0.897
CaO	CBR (%)	0.9003x + 6.152	0.935	0.0072	0.952
CaO	PI (%)	−3.415x + 19.44	0.963	0.0030	0.976
CaO	DFS (%)	−15.59x + 57.43	0.892	0.0157	0.988
CaO	OMC (%)	−1.398x + 13.28	0.947	0.0052	0.981
CaO	MDD (g/cm³)	0.0269x + 1.866	0.865	0.0221	0.941

The linear fits describe the plasticity and swell responses to FCS very well (Table 10, Fig. 3). Each 1% of FCS lowered the plasticity index by about 1.28 percentage points ($R^2 = 0.999$) and the differential free swell by about 1.92 percentage points ($R^2 = 0.997$), both with $p < 0.001$, which is consistent with the dilution of the active clay fraction by non-plastic slag discussed in Section 4.1. The CBR is less well described by a straight line ($R^2 = 0.895$) than by a parabola ($R^2 = 0.990$), and the MDD is poorly described by a line ($R^2 = 0.542$, $p = 0.156$) because both rise to a maximum and then flatten or fall. The fitted CBR parabola, $CBR = -0.01354x^2 + 0.5161x + 1.111$, reaches its maximum at 19.1% FCS, which lies at the upper end of the tested range, whereas the measured maximum is at 15% FCS. The measured CBR values at 15% and 20% FCS (6.10% and 5.91%) differ by only 0.19 percentage points, and the maximum of the fitted curve is correspondingly flat, so the 15% FCS content is retained as the measured optimum but the CBR cannot be said to be sharply peaked.

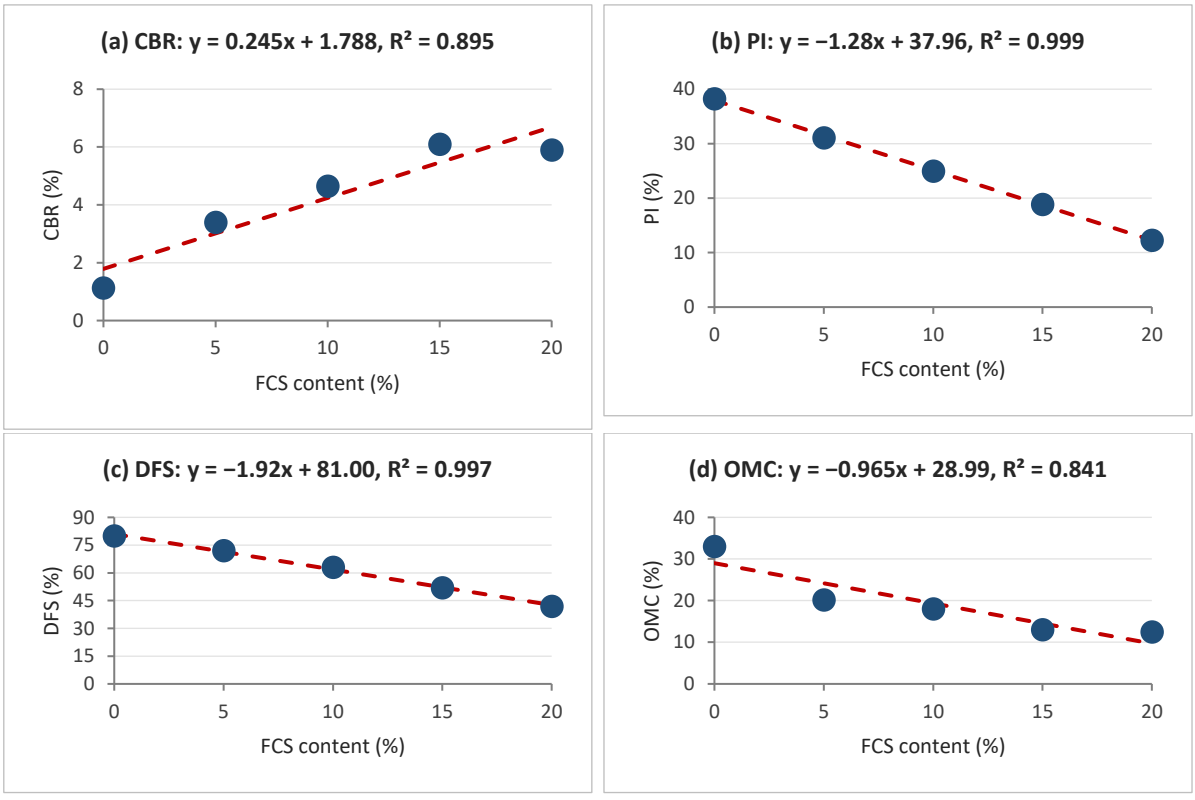


Figure 3. Linear regression of the measured responses on FCS content: (a) CBR; (b) plasticity index; (c) differential free swell; (d) optimum moisture content. Points are measured values; lines are least-squares fits

The CaO series shows the same pattern with steeper slopes (Table 10, Fig. 4). Each 1% of CaO lowered the PI by about 3.41 percentage points ($R^2 = 0.963$, $p = 0.003$) and the DFS by about 15.6 percentage points ($R^2 = 0.892$, p

= 0.016), and raised the CBR by about 0.90 percentage points (R^2 = 0.935, p = 0.007). The DFS response is more strongly curved than the PI response, since its quadratic R^2 (0.988) is well above its linear R^2 (0.892). The fitted quadratic for CBR on CaO, CBR = $-0.1556x^2 + 1.283x + 6.036$, has its maximum at 4.1% CaO, outside the tested range, so within 0–2.5% CaO the regression alone does not locate an optimum; the choice of 2.0% CaO rests on the measured CBR (8.24% at 2.0% and 8.12% at 2.5%), and the difference between these two values is small.

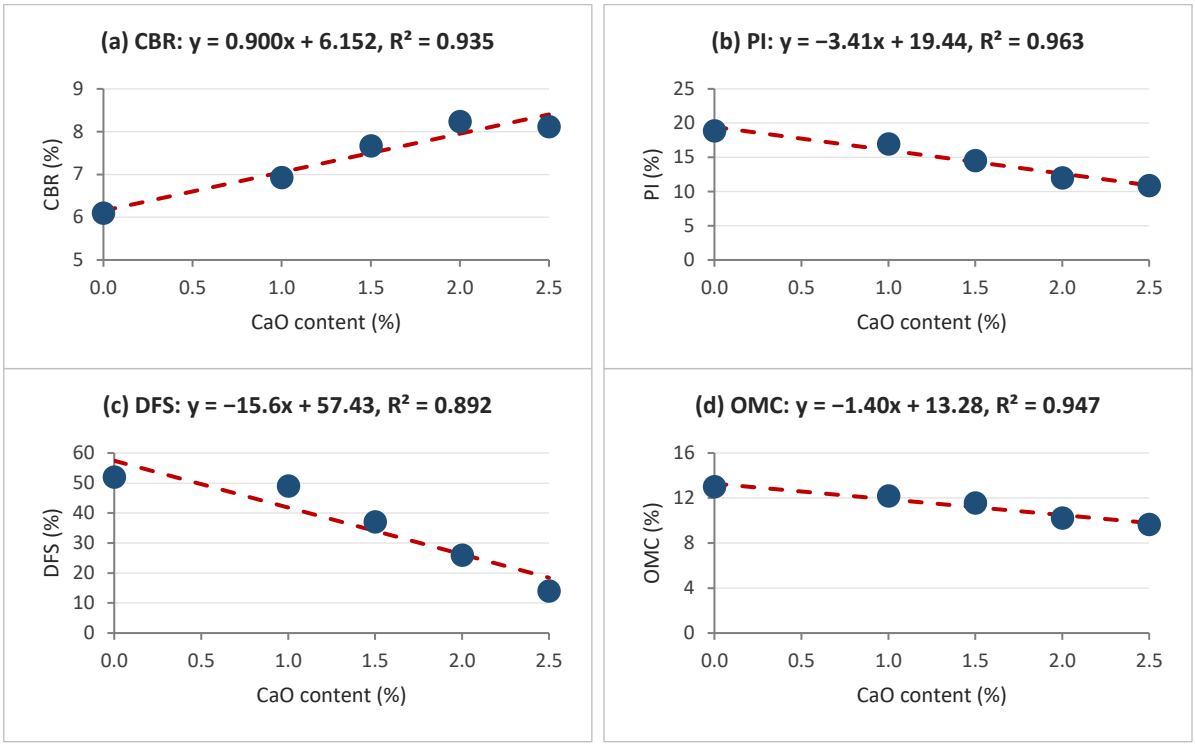


Figure 4. Linear regression of the measured responses on CaO content for the 15% FCS mix: (a) CBR; (b) plasticity index; (c) differential free swell; (d) optimum moisture content. Points are measured values; lines are least-squares fits

Figure 5 compares the second-degree polynomial fits of CBR with the measured values. In both series the polynomial follows the measured points closely, but the curvature of the CaO series, whose maximum falls outside the tested range, is controlled largely by the last two points, and the fit should therefore be used only for interpolation between 0 and 2.5% CaO.

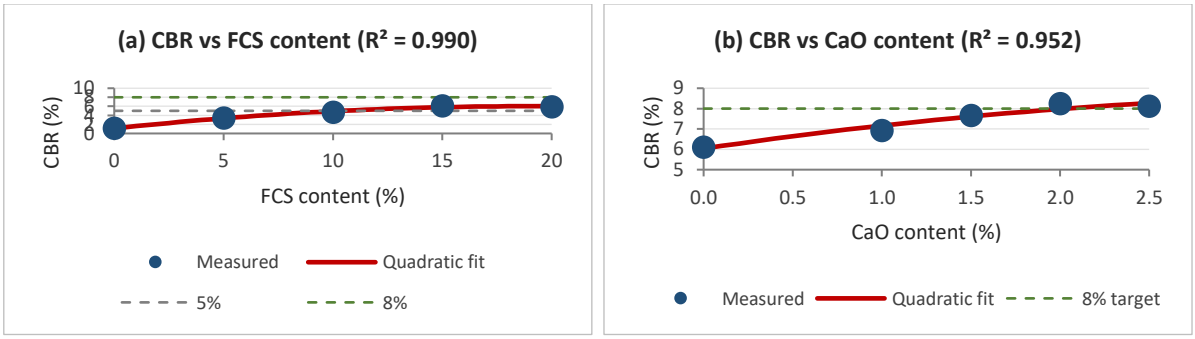


Figure 5. Second-degree polynomial regression of CBR: (a) FCS content, with the 5% and 8% CBR levels; (b) CaO content on the 15% FCS mix, with the 8% target

4.5 Mechanisms of improvement

The test results point to two complementary mechanisms. The first is physical. FCS is a dense, non-plastic and angular-to-rough material that replaces part of the clay, reduces the proportion of expansive clay minerals, lowers the water demand for compaction and provides a granular skeleton, which together increase density and CBR and reduce swell. The second is physico-chemical and is associated with CaO. Dissolved Ca^{2+} ions replace monovalent cations such as Na^{+} and K^{+} on the clay surfaces and raise the electrolyte concentration of the pore water. According to diffuse double layer theory, the thickness of the double layer decreases with increasing ion concentration and valence [1], so the particles flocculate and aggregate, which lowers swell and plasticity. The high pH produced by CaO may also release silica and alumina from the clay minerals and from the slag, which contains about 30% SiO_2 and 26% Al_2O_3, and these could react with calcium to form cementitious compounds, as in lime stabilisation [4]. The contribution of this pozzolanic reaction was not verified in the present work because no mineralogical or microstructural analysis (XRD, SEM) was performed, and it should be regarded as a plausible explanation rather than an established one.

4.6 Practical implications and limitations

The combination of 15% FCS and 2.0% CaO raised the CBR of the marine clay from 1.13% to 8.24%. A subgrade of this quality could be expected to allow a thinner pavement section than the untreated clay, and the use of 15% FCS by weight of soil provides an outlet for a large volume of an industrial by-product that is otherwise mostly disposed of at site. The economic benefit was not quantified here. The CBR of 8.24% obtained here is close to the 8.07% reported for the foundry sand–geopolymer mixture [24]. The plasticity-index reduction was smaller than that study's 76.5% (68.7% here), whereas the swell reduction was larger (67.5% here, against up to 58%). The two clays differ, so the comparison is only indicative. That study also used X-ray diffraction to confirm the mineralogical changes associated with strength gain [24], which is the analysis missing from the present work.

Several limitations should be noted. Only one marine clay was tested, and the specimens were remoulded and prepared under controlled laboratory conditions, so the results may not represent in-situ deposits. The durability of the treated clay under wetting and drying and its long-term strength gain were not investigated. The FCS contains 15% Cr_2O_3, and although the slag is insoluble in water, leaching of chromium from the treated soil was not evaluated and must be examined before field use. Finally, no pavement-scale or traffic-loading tests were carried out, and field trials are required to confirm the behaviour of the treated subgrade in service.

5. Conclusions

Laboratory tests on marine clay from Kakinada treated with ferrochrome slag (FCS) and calcium oxide (CaO), lead to the following conclusions.

1. The optimum additive contents were 15% FCS and 2.0% CaO. At 15% FCS the CBR and MDD reached their maximum values among the FCS mixes, and with 2.0% CaO they reached their maximum values among the FCS–CaO mixes.
2. FCS reduced the swelling and plasticity of the marine clay. At 15% FCS the differential free swell decreased by 35.0% (80% to 52%) and the plasticity index by 50.7% (38.3% to 18.9%). With 2.0% CaO the reductions reached 67.5% (to 26%) and 68.7% (to 12.0%), respectively.
3. The compaction characteristics improved markedly. At 15% FCS the OMC decreased by 60.6% (33.02% to 13.00%) and the MDD increased by 35.0% (1.378 to 1.860 g/cm³). With 2.0% CaO the OMC was 10.23% and the MDD 1.932 g/cm³ (a 40.2% increase over the untreated clay).
4. The CBR increased from 1.13% to 6.10% (an increase of 439.8%) with 15% FCS and to 8.24% (629.2%) with 15% FCS and 2.0% CaO. Both mixtures exceed the 5% minimum subgrade CBR of IRC:37-2012, and only the latter exceeds the 8% target adopted here, which is the IRC:37-2012 capping-layer minimum.
5. FCS together with a small dose of CaO is a technically effective and potentially economical means of stabilising marine clay subgrades while reusing an industrial waste. Future work should include field trials,

durability testing, mineralogical and microstructural analysis, leaching assessment for chromium, and the use of geosynthetic reinforcement and separators with the treated subgrade.

Author Contributions (CRediT)

Sajida Sulthana Mohammed: Conceptualisation; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualisation; Writing — original draft; Writing — review & editing.

D. Koteswara Rao: Conceptualisation; Project administration; Methodology; Validation; Resources; Supervision; Writing — review & editing.

Declaration of Competing Interests

The authors confirm the absence of any financial or personal competing interests that may have influenced the findings presented herein.

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Data Availability

The raw data supporting the conclusions of this article are available from the corresponding author upon reasonable request.

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