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Utilization of steel slag for stabilization of subgrade soil

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Abstract. As a developing nation, India is presently undergoing transformation. With rising population and rapid urbanization, demand for sustainable transportation facilities is skyrocketing. Highway engineers frequently struggle to find the right material for highway construction. On other hand, Rapid urbanization has led to a surge in infrastructure and development projects, skyrocketing steel consumption. India is the second-largest steel producer, trailing only China. Integrated steel plants in India produce 2-4 tonnes of slag per tonne of steel, which is then stockpiled. Waste disposal in an environmentally friendly manner is a major concern. Current study investigates possible utilization of steel slag for stabilization of dredged soil when used along with traditional stabilizing agent. Proposed study helps identify the effect of addition of slag and cement on strength characteristics of composite mix. It is also extended to investigate the effect of curing on strength characteristics.
Current study also tries to analyze the effect of providing 500 mm thick stabilized capping subgrade on design parameters such as Vertical compressive strain, horizontal tensile strain at critical locations with the help of IITPAVE software.

Keywords: Strength characteristics, UCS, CBR, IITPAVE

1 Introduction

In India, unavailability of suitable material for construction of highway severely hampers the schedule and cost of the project. This problem can be solved by utilizing the waste by products such as steel slag, copper slag, zinc slag, bottom ash. As per world steel association, 1951 million tonne of steel is produced in year 2021. During the production of steel, 2 types of slag namely Blast furnace slag and steel making slag. In India, Annual rate of slag generation is higher than the world average [1] thus tremendous quantity of waste which is usually dumped in the premises of the integrated steel plant. The use of processed steel slag in road construction allows for sustainable waste management and reduces reliance on perishable natural aggregates.

Several studies have been carried out on utilization of waste by-products in construction of flexible pavement. Akinwumi et al. [2] concluded that steel slag can be effectively used for soil stabilisation in order to meet Nigerian standards for the utilisation of various component layers of pavements. Tiwari et al. [3] provided an Indian perspective on the use of steel slag. Aldeeky et al. [4] investigated the efficacy of steel slag in the context of highly plastic soil and discovered an improvement in the geotechnical properties of such soil when used in the pavement subgrade. C3S, C2S, C4AF, and C2F present in steel slag impart cementitious properties [5]. Athulya et al. [6], Ahirwar et al. [7] discussed the suitability of soil-slag mixtures for use in various layers of pavement.

Development of strength of the stabilized mix depends on the % of admixture used and curing period. Poh [8] identified that development of strength for soil stabilized with basic oxygen steel slag fines requires long curing period. Sabat et al. [9] examined the effect of curing on an expansive soil stabilized with marble waste and rice husk ash. Okagbue [10] investigated the effect of 7 day and accelerated 24 hours curing on soil stabilized with marble dust. Athulya et al [6] identified that strength of the soil stabilized with steel slag, cement, nano silica improves with curing period.

2 Material

The experimental investigation makes use of three distinct materials: dredged soil, steel making slag, and cement. The soil used in this study was dredged from banks of the Uran River in Maharashtra. The basic properties of the dredged soil are shown in Table 1. In this study, ordinary Portland cement was used. Steel making slag is provided by Metarolls and Commodities Pvt. Ltd, Maharashtra. Slag is classified as a silty material with a low plasticity.

Table 1. Properties of dredged soil

Property	Value
SG: Specific gravity	2.45
LL: Liquid limit	68.1
PL: Plastic limit	32.8
PI: Plasticity index	35.3
Soil classification	CH
MDD: Maximum dry density (kg/cm3)	1.46
OMC: Optimum moisture content (%)	27.5
UCS: Unconfined compressive strength (kPa)	118.6

Sieve analysis and hydrometer testing were used to determine particle size. The particle size distribution of clay and steel making slag is depicted in Figure 1. The results of chemical analysis carried out using an X-ray fluorescence test shows that silicon dioxide, aluminium oxide, iron oxide, and calcium oxide are the most abundant elements in the clay. Steel making slag was primarily composed of Silicon dioxide, Aluminium oxide, ferrous oxide, calcium oxide and magnesium oxide.

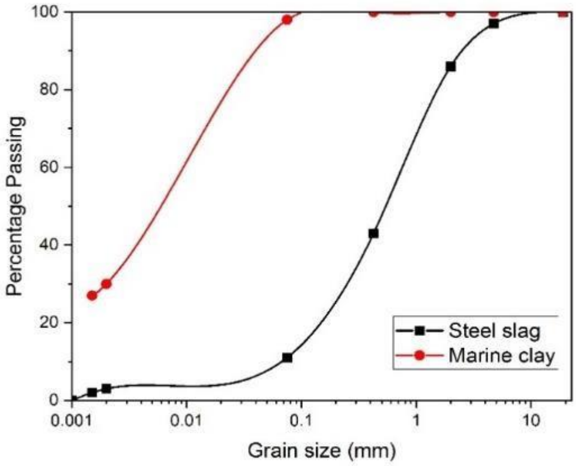

Fig. 1. Particle size analysis of dredged soil and steel making slag

3 Experimental programme

The current study looks into the possible utilization of steel making slag for stabilisation of clayey subgrade. The geotechnical investigation involved determining the strength characteristics of composite mix in terms of unconfined compressive strength (UCS) and California bearing ratio (CBR). The dredged soil was mixed with various proportions of steel slag. The laboratory investigations were expanded to include the strength characterization of dredged soil stabilised with various proportions of steel slag and cement. Percentage of steel slag was varied in the range of 10-40% whereas cement in the range of 4-8%.

Study is also stretched to evaluate the effect of curing period on unconfined compressive strength of the composite mix containing soil-slag-cement.

4 Proposed Model for Analysis of flexible pavement

The current analysis considers compacted subgrade with higher CBR and natural subgrade with lower CBR as a two-layered system as shown in fig.1.

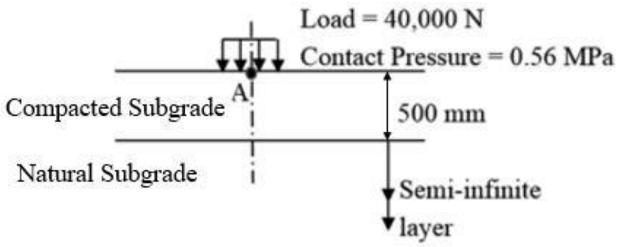

Fig. 2. Two Layered system of compacted placed over natural subgrade

Elastic modulus of the both the layers are estimated using relationship given by Powell et al [11]

$$E = 10^{*} \text{ CBR (Mpa) if CBR} <= 5 \qquad \text{(Eq.1)}$$

$$E = 17.6 \text{ CBR}^{0.64} \text{ (Mpa) if CBR} > 5 \qquad \text{(Eq.2)}$$

The maximum surface deflection caused by a single wheel load of 40000 N and a contact pressure of 0.56 Mpa for a two-layer system consisting of a 500 mm thick subgrade laid over natural soil is calculated using the IITPAVE software. The equivalent single layer's resilient modulus is then calculated using equation

$$M_{RS} = \frac{2(1-\mu^2)\,pa}{\delta} \qquad \text{(Eq.3)}$$

Where,
p = Contact pressure
a = Radius of circular contact area
μ = Poisson's Ratio

According to IRC 37- 2018, the design is based on the effective resilient modulus MRS and not the CBR.However effective CBR can be calculated using Equation (1) and (2).

Composition of conventional pavement is made based on catalogue provided in IRC 37-2018 which is based on effective CBR. To run the analysis of flexible pavement on IITPAVE software, The modulus of different layers of pavement are calculated based on the IRC: 37-2018 guidelines. For the BC and DBM, VG 40 bitumen with air void content (Va) of 3% and effective bitumen content by volume (Vbe) = 13% is considered for the analysis. Based on the consideration, the modulus value of bituminous (MR) layer for all the cases are 3000MPa [12]

Modulus of granular layer was calculated from the following formula given in IRC.

$$M_{RGRAN} = 0.2\,(h)^{0.45} \times M_{RSUPPORT} \qquad \text{(Eq.4)}$$

Where,

h= thickness of granular layer in mm

M_{RGRAN} = Resilient modulus of the granular layer (MPa)

$M_{RSUPPORT}$ = Resilient modulus of the supporting layer (MPa)

The rutting condition of the pavement is classified as critical or failure when the average rut depth is 20 mm or greater. The IRC recommends considering the equivalent number of standard axle load repetitions that the pavement can withstand before developing rut depths of 20 mm or greater.

The maximum strain at top of the subgrade is calculated on the basis of the rutting model for 90% reliability as per IRC:37-2018.

$$N_R = 1.4100 \times 10^{-8} \left[{}^{1/}\varepsilon_v \right]^{4.5337} \quad \text{(Eq.5)}$$

Where;

NR = subgrade rutting life (cumulative equivalent number of 80 kN standard axle loads that can be served by the pavement before the critical rut depth of 20 mm or more occurs)

εv = vertical compressive strain at the top of the subgrade calculated using linear elastic layered theory by applying standard axle load at the surface of the selected pavement system

The maximum strain at the bottom of the bituminous layer is calculated on the basis of the Fatigue model for 90% reliability as per IRC 37-2018.

$$Nf = = 0.5161*C*10^{-4}[{}^{1/}\varepsilon_t]^{3.89}*[1/M_{RM}]^{0.854} \quad \text{(Eq.6)}$$

Where,

$$M = 4.84\ (V_{be}/V_a+V_{be})-0.69 \quad \text{(Eq.7)}$$

V_a = per cent volume of air void in the mix used in the bottom bituminous layer considered 3

V_{be}= per cent volume of effective bitumen in the mix used in the bottom bituminous layer considered 13

Pursuant to the analysis of flexible pavement as per IRC:37-2018, the IITPAVE software analysis is carried out to determine the vertical and horizontal strain at the critical location of the traditional layer system for design traffic of 50 msa. The vertical compressive strain and horizontal tensile strain so obtained from IITPAVE software is then compared with the permissible strain to check the feasibility.

5 Results of Experimental programme

5.1 Unconfined compressive strength of the composite mix.

The Unconfined compressive strength test was conducted on various composite mixes containing dredged soil and steel making slag. From the fig 3 it can be concluded that, unconfined compressive strength of the mix increases after addition of steel slag up to 30%. Akinwumi et al. [2], Aldeeky et al. [4] also observed that the unconfined compressive strength of subgrade soil improves with addition of steel slag. Similar pattern can be seen in case of samples tested on 7th and 28th day. Furthermore, the strength of the soil-slag mixes increases with the increase in curing period.

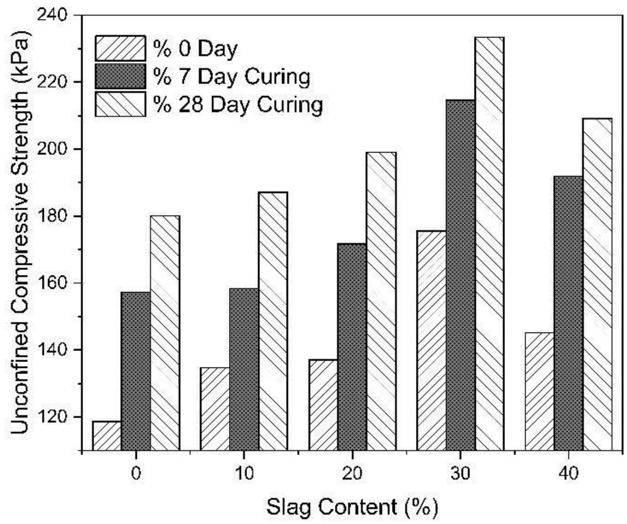

Fig. 3**.** Variation in UCS of the soil-slag mix for 0,7,28-day curing.

UCS test were also conducted on mix containing soil-slag-cement. From the fig 4 it can be concluded that, UCS of the mix increases significantly after addition of cement. Furthermore, the strength of the mix improves with the curing period. Athulya et al. [6] observed significant improvement in strength of the soil-slag mix when admixed with the conventional stabilizer like cement.

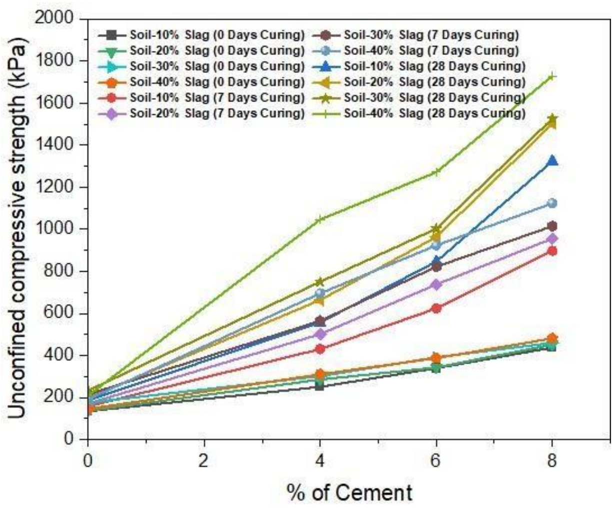

Fig. 4. Variation in UCS of the soil-slag-cement mix for 0,7,28-day curing.

5.2 California Bearing ratio of composite mix

The California bearing ratio test was conducted on various composite mixes containing, steel making slag and cement. Fig 5 suggests that there is no significant improvement in CBR when soil is admixed with the slag alone. Whereas after addition of cement, CBR of the mix increases significantly. Athulya et al. [6] also observed significant improvement in CBR of the soil-slag mix after addition of cement.

For a composite mix containing 4% cement, the CBR of a soil-slag-cement composite increases as slag content approaches 30%. Similar trend can be observed in case of mix containing 6% and 8% cement.

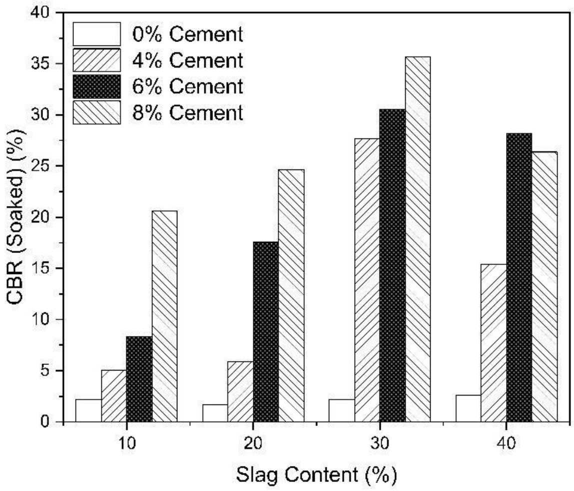

Fig. 2. California bearing ratio of composite mix

6 Analysis of flexible pavement on stabilized subgrade

Analysis of Flexible pavement is based on traffic volume, wheel load and characteristics of the materials used for the construction. Different methods of design of flexible pavement include: CBR method, Asphalt Institute method, Austroads, U.K. Road Note 29 and IRC: 37- 2001, 2012 and 2018. In the present study, IRC: 37-2018 guidelines based on the cumulative standard axial load is used.

Based on the laboratory investigations, the soaked CBR values of some of the combinations selected for the analysis is shown in table 2.

Table 2. CBR values of dredged soil stabilised with different stabilizers

S. No	Type of stabilised Soil	Soaked CBR (%)
1.	Dredged soil	2.15
2.	Dredged soil + 30% steel slag +4% Cement	27.67
3.	Dredged soil + 30% steel slag +6% Cement	30.53
4.	Dredged soil + 30% steel slag +8% Cement	35.67

From the laboratory investigation it is observed that CBR of the natural subgrade is lower than the permissible limit prescribed by IRC standards. Thus alternative 500 mm thick capping subgrade should be laid having greater CBR. In such case effective CBR of the single layer subgrade which is equivalent to combination of compacted subgrade and natural subgrade should be laid. In current investigation, it is proposed to construct the 500 mm thick layer of the stabilized clay mixes having higher CBR. IRC standards suggests that it is effective resilient modulus value and not the CBR is used for design of the flexible pavement. Effective CBR of the single layer subgrade is equivalent to combination of subgrade layer and compacted subgrade (Stabilized soil) is shown in table 3.

The thickness of the flexible pavement is estimated using IRC 37-2012,18 standards considering conventional layer system and is based on effective CBR values of the various mixes for design traffic of 50 msa and is summarized in table 3.

Table 3. Thicknesses of different layer for the conventional flexible pavement

Sr. No	Stabilised soil mix	Effective CBR (%)	Total Thickness (mm)	GSB (mm)	Base (mm)	Binder (mm)	Surface (mm)	Reference
1	Dredged soil	2.15	911	448	250	173	40	IRC 37-2012 [13]
2	Dredged soil + 30% steel slag +4% Cement	10.96	593	200	250	103	40	IRC 37-2018 [12]
3	Dredged soil + 30% steel slag +6% Cement	11.59	591	200	250	101	40	
4	Dredged soil + 30% steel slag +8% Cement	12.65	587	200	250	97	40	

Thickness of the flexible pavement is reduced significantly when 500 mm thick stabilized compacted subgrade is placed over the natural subgrade soil. When soil-30% slag-4% cement mix is used as a compacted capping subgrade, thickness of the flexible pavement reduces by 34.90%. Whereas for mix containing 6% cement and 8% cement, reduction in thickness of about 35.12% and 35.56% can be observed respectively.

The resilient modulus of the various layers of flexible pavement considering different mixes of subgrade soils is calculated as per IRC 37-2018 and is shown in Table 4.

Table 4. Resilient modulus for various layer of flexible pavement considering different stabilised soil subgrade

Sr. No.	Stabilised soil	Modulus values for different layers (MPa)		
		Subgrade	Granular sub base and base	Bituminous layer
1.	Dredged soil + 30% steel slag +4% Cement	81.477	254.689	3000
2.	Dredged soil + 30% steel slag +6% Cement	84.448	263.976	3000
3.	Dredged soil + 30% steel slag +8% Cement	89.335	279.252	3000

Flexible pavements are subjected to fatigue and rutting damages due to the repetitions of heavy axle wheel load. Vertical compressive strain on top of the subgrade, corresponding to standard axle load repetitions, is indicative of failure of natural subgrade. Vertical compressive strain on top of the subgrade and horizontal tensile strain at the bottom of the bituminous layer are considered critical parameters that must be controlled to ensure satisfactory performance of the flexible pavement in terms of subgrade rutting and bottom-up cracking of bituminous layers. Based on the modulus of different layers and their thickness, the IITPAVE software analysis is carried out to determine the vertical and compressive strain at the critical location of the traditional layer system for design traffic of 50 msa.

Table 5. Comparison between permissible strain and actual strain obtained using IIT Pave software

Sr. No.	Stabilized soil mix	Strain	Permissible Limit (As per IRC 37)	Actual Strain (IIT Pave)	Remark
1	Dredged soil + 30% steel slag +4% Cement	Horizontal tensile strain	203.1×10^{-6}	$173.0*10^{\wedge -6}$	Safe
		Vertical compressive strain	371.69×10^{-6}	$268.8*10^{\wedge -6}$	Safe
2	Dredged soil + 30% steel slag +6% Cement	Horizontal tensile strain	203.1×10^{-6}	$171.7*10^{\wedge -6}$	Safe
		Vertical compressive strain	371.69×10^{-6}	$263.3*10^{\wedge -6}$	Safe
3	Dredged soil + 30% steel slag +8% Cement	Horizontal tensile strain	203.1×10^{-6}	$171.5*10^{\wedge -6}$	Safe
		Vertical compressive strain	371.69×10^{-6}	$257.0*10^{\wedge -6}$	Safe

In all the above-mentioned cases, the value of actual strain calculated using IIT Pave software is less than the allowable strain. From table 5. It can be observed that conventional design by using IRC 37-2018 methodology can be considered safe rendering good serviceability.

7 Summary of conclusions

The aim of the experimental research conducted for this paper was to explore the potential of using steel slag to stabilize subgrade soil. It involved characterizing the structural strength after it had been stabilised with steel making slag and cement. Pursuant to the analysis of flexible pavement as per IRC:37-2018, the IITPAVE software analysis is carried out to determine the vertical and compressive strain at the critical location of flexible pavement for design traffic of 50 msa. From the experimental and analytical work carried out in present study following broad conclusions to be drawn.

- Unconfined compressive strength of the slag stabilized dredged soil improves after addition of steel slag up to 30%.
- UCS of the mix increases with curing period.

- There is no significant improvement in strength characteristics like unconfined compressive strength and California bearing ratio, when soil is admixed with the slag alone. Whereas after addition of cement, CBR of the soil-slag-cement composite mix increases significantly.
- When soil stabilized with steel slag and cement is used as capping subgrade, thickness of the flexible pavement reduces significantly.
- When stabilized soil is used as a capping subgrade, the actual strain calculated using IIT Pave software falls within permissible limits thus can be considered safe rendering better serviceability.

The current study demonstrates the efficacy of using industrial waste such as steel slag to improve the engineering properties of weak soil when combined with a conventional stabiliser. The abundant use of steel making slag, in highway construction can be made in a sustainable manner, reducing environmental concerns.

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