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Sustainable Ground Improvement Using Industrial Waste: Steel Slag as Granular Columns

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Abstract

The increasing demand for infrastructure development on weak and compressible soils has necessitated the adoption of effective ground improvement techniques. At the same time, the rapid growth of the steel industry has resulted in the generation of huge quantities of steel slag, posing significant environmental and waste management issues. This paper focuses on the sustainable utilization of steel slag as a substitute material for granular columns in ground improvement applications. This paper involves an experimental investigation to evaluate the effectiveness of steel slag columns in enhancing the engineering properties of soft soils. The study also examined the influence of several factors, including the properties of column materials, column diameter, number of columns, and column arrangement, on the lateral load-carrying capacity of granular column–soil composite systems. To evaluate these effects, a series of large-scale direct shear tests was conducted under different normal stress conditions. These tests helped in understanding the behavior and strength characteristics of the composite system when subjected to lateral loading. Steel slag was selected as the column material because of its high strength, rough and angular particle shape, and excellent drainage properties, which are expected to enhance the engineering performance of weak soils. The findings of the study indicate that steel slag has strong potential as a substitute for conventional natural aggregates used in granular column applications. The use of steel slag in ground improvement techniques offers multiple benefits. In addition to improving soil strength and stability, it provides productive use for an industrial by-product that would otherwise require disposal. This helps reduce environmental impacts, minimizes the consumption of natural aggregate resources, and supports sustainable construction practices. Overall, the study highlights the role of steel slag in promoting environmentally responsible geotechnical engineering and contributing to the principles of a circular economy.

Keywords: Ground improvement, steel slag, shear strength, soil stabilization

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INTRODUCTION

Rapid urbanization and infrastructure development have significantly increased the demand for construction on weak and compressible soil. These soils often exhibit low bearing capacity, excessive settlement, and poor shear strength, making them unsuitable for supporting heavy structures without prior improvement. Ground improvement techniques have therefore become essential in geotechnical engineering to enhance soil properties and ensure the stability and safety of structures. Among the various methods available, the granular column technique is widely used because of its effectiveness in improving the load-bearing capacity, reducing settlement, and accelerating the consolidation of soft soils. Traditionally, granular columns are constructed using natural aggregates, such as sand and gravel.

The massive extraction of finite materials raises concerns about planetary health and high project budgets. Today, architects demand better building practices to protect homes. Researchers have examined industrial waste to assist with structural tasks because current waste needs to be reused. Steel slag serves as a solid option for use in projects. Factories create this raw byproduct while melting iron into plates. We convert discarded metal scraps into stable parts for civil work. Steel slag possesses favorable engineering properties, such as high strength, durability, angularity, and good drainage characteristics, making it a potential alternative to conventional granular materials. The use of steel slag in granular columns not only helps improve the engineering behavior of weak soils but also contributes to effective waste management and reduction in environmental pollution. Using industrial scrap during soil reinforcement tasks offers clear fiscal gains while lowering the broader environmental impact [1–3].

This study experimentally investigated the use of steel slag as a substitute material for granular columns in ground improvement. The objective of this study was to evaluate the effectiveness of this method in enhancing soil properties, such as bearing capacity, settlement characteristics, and overall performance. The findings of this study aim to promote sustainable geotechnical practices and provide an alternative solution for the reuse of industrial waste in construction [4–6].

STEEL SLAG

Steel slag is an industrial byproduct of steel manufacturing. It is generated when impurities present in raw materials, such as iron ore, scrap steel, and fluxing agents, react and separate from the molten metal during steelmaking. The composition and properties of steel slag vary depending on the production method. Based on the steel production process, steel slag is generally categorized into three main types: Basic Oxygen Furnace Slag (BOFS), Electric Arc Furnace Slag (EAFS), and Ladle Refining Slag (LFS). Owing to its strength and durability, steel slag has gained considerable attention as a potential material for various civil and geotechnical engineering applications. Steel slag is a hard, dense, and durable material with high angularity and a rough surface texture. These properties make it suitable for various engineering applications. It typically contains compounds of calcium, silica, iron, and magnesium, which contribute to its strength and stability. Owing to its good mechanical properties, steel slag has been widely used in road construction, cement manufacturing, and as an aggregate in different civil engineering works. However, large quantities of steel slag are produced annually, leading to disposal and environmental challenges, such as land occupation and potential soil and water contamination [7–10].

In recent years, steel slag has gained attention in geotechnical engineering as an alternative material for soil stabilization and ground improvement applications. Its high strength, permeability, and interlocking characteristics make it a promising substitute for conventional granular materials in applications such as granular columns and embankments. Thus, the effective utilization of steel slag not only enhances engineering performance but also supports sustainable development by reducing environmental impact and conserving natural resources (Figure 1) [11, 12].

Figure 1. (a) and (b) Steel slag.

OBJECTIVES OF THE STUDY

1. To determine the index properties (grain-size distribution and specific gravity) of steel slag,
2. To determine mechanical properties (compaction test) of steel slag,
3. To determine the shear strength of a single steel slag column.

Geotechnical properties of steel slag present details in Table 1.

EXPERIMENTAL PROGRAMME

Evaluating the engineering properties of steel slag is essential for developing reliable design guidelines for its use in different geotechnical and construction applications. Although steel slag has gained attention as an alternative construction material, the available information regarding its physical and mechanical characteristics remains limited. Therefore, the present study was conducted to provide additional experimental data and improve the understanding of steel slag behavior. As part of this research, a series of large-scale direct shear tests was performed to investigate the performance of soil reinforced with steel slag granular columns with and without geosynthetic encasement. A large direct shear apparatus with dimensions of 30 cm × 30 cm × 14 cm was utilized, allowing the testing of composites containing relatively large steel slag particles. The specimens were subjected to normal stresses of 33, 65, and 130 kPa, and shearing was performed under displacement-controlled conditions at a constant rate of 1 mm/min. The test results helped assess the shear strength characteristics and overall behavior of steel slag column–soil composite systems under different loading conditions (Table 2).

The effect of the column diameter or area replacement ratio (Ar) on the shear strength parameters of the column-soil composites was investigated in all the test groups. Ar is defined as the ratio of the granular column area to the total area of the shear box. It should be noted that a single granular column was placed at the center of the shear box (Table 3 and Figures 2–4).

$$\%\ of\ Area\ Ratio = \frac{Ratio\ of\ granular\ column\ area}{Total\ area\ of\ shear\ box} \times 100$$

Area of direct shear apparatus box = 30 × 30 cm = 900 cm^2

Area of 10 cm dia. granular column = $\frac{x}{4} \times 10^2 = 78.53\ cm^2$

$\%\ of\ Area\ ratio = \frac{78.53}{900}$ x 100 = 8.7%

Table 1. Geotechnical properties of steel slag.

S.N.	Property	Values
1	Specific gravity	2.70
2	Maximum dry density (kg/m^3)	19.51
3	Minimum dry density (kg/m^3)	14.48
4	Friction angle	43
5	Cohesion	3.82
6	Hardness	6-7
7	Porosity	Up to 3

Table 2. Outline of experimental programme.

S.N.	Properties	Experiments
1	Index	a. Grain-size distribution b. Specific gravity
2	Mechanical	a. Compaction b. Direct shear test

Table 3. Details of direct shear test.

Test group	Type of column material	Column diameter (cm)	Area replacement ratio, Ar (%)	No. of columns	Normal stress (kPa)
Group 1	Coarse Steel Slag	10	8.7	1, 2, 3	33, 65, 130

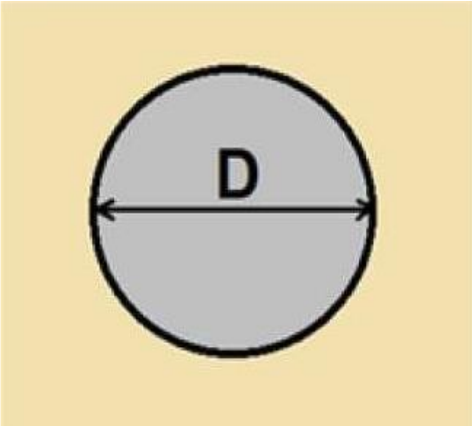

Figure 2. Column diameter, D = 10 cm.

Figure 3. Fine steel slag.

Figure 4. Coarse steel slag.

RESULT

Grain Size Distribution

This test was conducted to evaluate the physical characteristics of steel slag and assess its suitability for various geotechnical engineering applications. One of the key laboratory tests performed was sieve analysis of coarse aggregates, which is widely used to determine the gradation of aggregate materials. This test helps in understanding the distribution of particle sizes present in a sample by separating the material through a series of standard sieves. The results obtained are useful for checking whether aggregates meet specified design criteria, quality standards, and production control requirements. Proper gradation of aggregates plays an important role in ensuring the strength, stability, and overall performance of engineering structures, as shown in Figures 5–8.

From the graph,

a. Coefficient of uniformity, $Cu = D_{60}/D_{10} = 13.41/7.51 = 1.786$
b. Coefficient of curvature, $Cc = (D_{30})^2/(D_{60} \times D_{10}) = 1.223$

Specific gravity is described in Table 4.

Compaction Test

Standard Proctor test is described in Table 4.

- Maximum dry density = 1.534 g/cm^3 and optimum moisture content = 10%.

Shear strength is described in Figures 7 and 8.

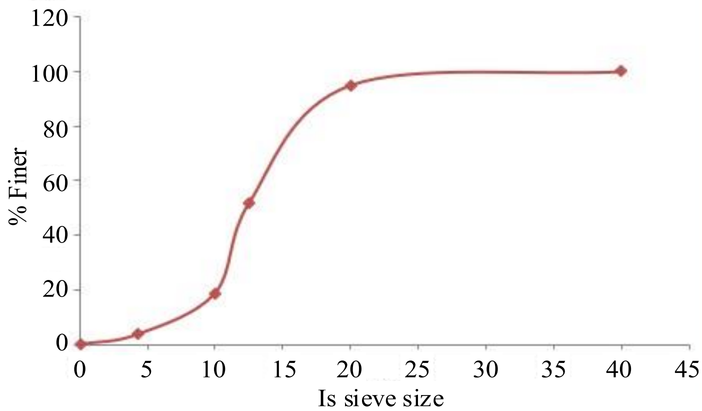

Figure 5. Particle size distribution curve for coarse steel slag.

Table 4. Observations and calculations for specific gravity of soil.

S.N.	Observations and calculations	Determination no.		
		1	***2***	***3***
1	Basket no.	1	2	3
2	Room temperature	27°C	27°C	27°C
3	Weight of saturated aggregate suspended in water with basket (W_1) (g)	2062	2060	2061
4	Weight of basket suspended in water (W_2) (g)	745	745	745
5	Weight of saturated surface dry aggregate in air (W_3) (g)	2002	2003	2002
6	Weight of oven-dry aggregate (W_4) (g)	1997	1996	1996
7	Weight of saturated aggregate in water = $W_1–W_2$ g	1317	1315	1316
8	Weight of water equal to the volume of the aggregate = $W_3–(W_1–W_2)$ g	685	688	686
9	Specific gravity, G = $W_3/(W_3–(W_1–W_2)$	2.92	2.91	2.92
10	Apparent specific gravity = $W_4/(W_4– (W_1–W_2))$	2.94	2.93	2.93
11	Water absorption = $((W_3–W_4)/W_4) \times 100$	0.25	0.35	0.30
Results of specific gravity of coarse steel slag at 27°C		**2.916**		

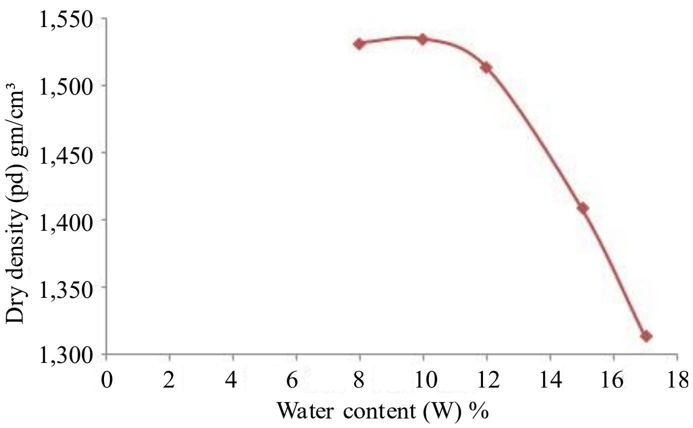

Figure 6. Compaction curve—standard Proctor test.

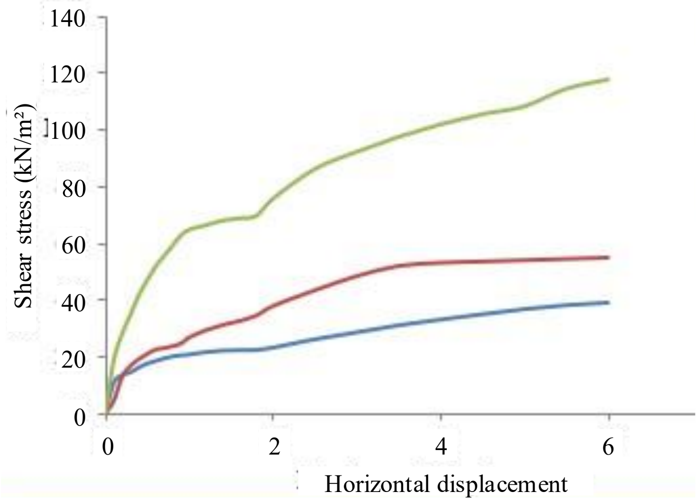

Figure 7. Horizontal displacement versus shear stress.

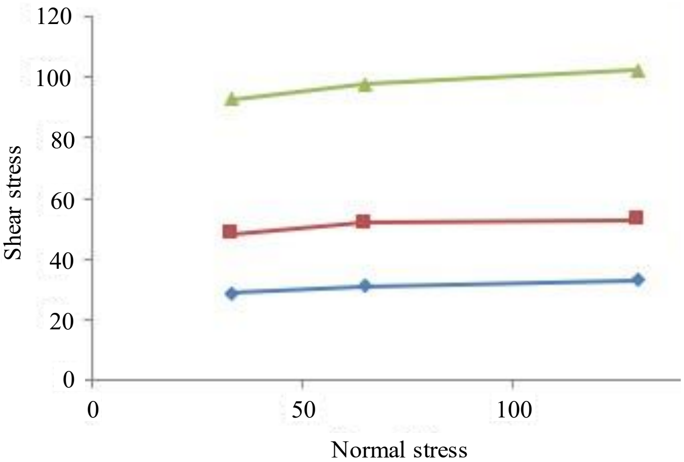

Figure 8. Normal stress Vs shear stress.

CONCLUSION

Based on the results, the following conclusions can be drawn:

1. Laboratory investigations were conducted to evaluate the index properties of steel slag and its potential use in geotechnical engineering applications. The specific gravity of the steel slag was determined to be 2.916 at 27°C, indicating that it is a relatively dense material. Although a higher specific gravity is often associated with greater strength, the suitability of steel slag for engineering applications cannot be assessed solely based on this parameter. A complete evaluation requires the determination of its mechanical and engineering properties.
2. The compaction characteristics of the steel slag were studied using the Standard Proctor Test. The results showed a Maximum Dry Density (MDD) of 1.534 g/cm³ and an Optimum Moisture Content (OMC) of 10%. These values indicate that steel slag can achieve satisfactory compaction when the appropriate moisture content is maintained during the field application.
3. The study revealed that the use of steel slag columns as a ground improvement technique significantly enhanced the shear strength of the soil. Compared with conventional sand columns, steel slag columns exhibited better performance and higher strength improvement. This demonstrates the effectiveness of steel slag as an alternative stabilizing material for weak-soil stabilization.
4. Experimental observations further confirmed that the steel slag columns contributed to improving the lateral load-carrying capacity of the soil. The arrangement pattern of the granular columns had only a minor influence on the overall shear strength when the area replacement ratio remained

constant. However, the columns aligned parallel to the shear direction exhibited slightly higher cohesion values, which may be due to the edge and shadowing effects. Overall, the results suggest that steel slag columns are a promising and sustainable solution for soil stabilization and ground-improvement projects.

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