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Research paper

Application of steel slag in stabilizations of expansive soil: an experimental study

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Abstract: This study was carried out to evaluate the effect of steel slag (SS) as a by-product as an additive on the geotechnical properties of expansive soil. A series of laboratory tests were conducted on natural and stabilized soils. Steel slag (SS) was added at a rate of 0, 5, 10, 15, 20, and 25% to the soil. The conducted tests are consistency limits, specific gravity, grain size analysis, modified Proctor compaction, free swell, unconfined compression strength, and California Bearing Ratio. The Atterberg limit test result shows that the liquid limit decreases from 90.8 to 65.2%, the plastic limit decreases from 60.3 to 42.5%, and the plasticity index decreases from 30.5 to 22.7% as the steel slag of 25% was added to expansive soil. With 25% steel slag content, specific gravity increases from 2.67 to 3.05. The free swell value decreased from 104.6 to 58.2%. From the Standard Proctor compaction test, maximum dry density increases from 1.504 to 1.69 g/cm3 and optimum moisture content decreases from 19.77 to 12.01 %. Unconfined compressive strength tests reveal that the addition of steel slag of 25% to expansive soil increases the unconfined compressive strength of the soil from 94.3 to 260.6 kPa. The California Bearing Ratio test also shows that the addition of steel slag by 25% increases the California Bearing ratio value from 3.64 to 6.82%. Hence, steel slag was found to be successfully improving the geotechnical properties of expansive soil.

Keywords: expansive soil, geotechnical parameters, soil stabilization, steel slag

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1. Introduction

Expansive soils are problematic in nature due to the existence of montmorillonite clay minerals. It has a high tendency to volume change upon a change in moisture content, which is known as swelling potential [1]. Building civil engineering structures, such as bridges, highways, roads, corridors, and railroads, on problematic soils can be very dangerous. This is due to the low compressive and shear strength and high compressibility of these soils, which can lead to structural collapse [2, 3].

As a result, many scholars have suggested various methods to improve expansive soil. Physical improvement and chemical treatment are the most significant methods of improving expansive soil [4]. Physical improvement is mainly used to improve the engineering properties of expansive soil by mixing it with coarse materials, such as sand, gravel, slag, etc. [5]. Chemical treatment is used to improve the physical and mechanical indices of expansive soil by inducing a physicochemical reaction in the expansive soil with admixtures such as fly ash, cement, lime, etc. [6]. Many scientists and engineers have carried out detailed studies of the physical and mechanical properties of improved expansive soils [7–18]. Steel slag (SS) waste is one of the materials from steel factories used for different purposes in the construction industry, such as in mortar road base material [19, 20], cement manufacturing [21, 22] and soil improvement [23–27]. Numerous studies have been conducted by various researchers on the use of steel slag to improve the engineering properties of weak soils [27–30].

This study is an attempt to improve the geotechnical engineering properties of expansive soils using the by-product of steel slag with various percentages.

2. Materials and methodology

2.1. Materials

2.1.1. Expansive soil

In Jimma, Ethiopia, soil samples were collected for the study. The soil samples were taken 1.5 m below the natural ground surface and kept in plastic bags to maintain their field moisture content. According to the Unified Soil Classification System (USCS), the sample was classified as high plasticity (CH) clay based on the test results. Figure 1 depicts the particle size distribution of the soil sample, and Table 1 summarizes the soil's geotechnical properties.

2.1.2. Steel slag

Steel slag is a waste product produced during the manufacturing of steel. It's created when molten steel is separated from impurities in steel-making furnaces. The steel slag used in this study was produced in Ethiopia by the Ethiopian Steel Company. The particle size distribution of the crushed aggregates of steel slag used is depicted in Figure 1.

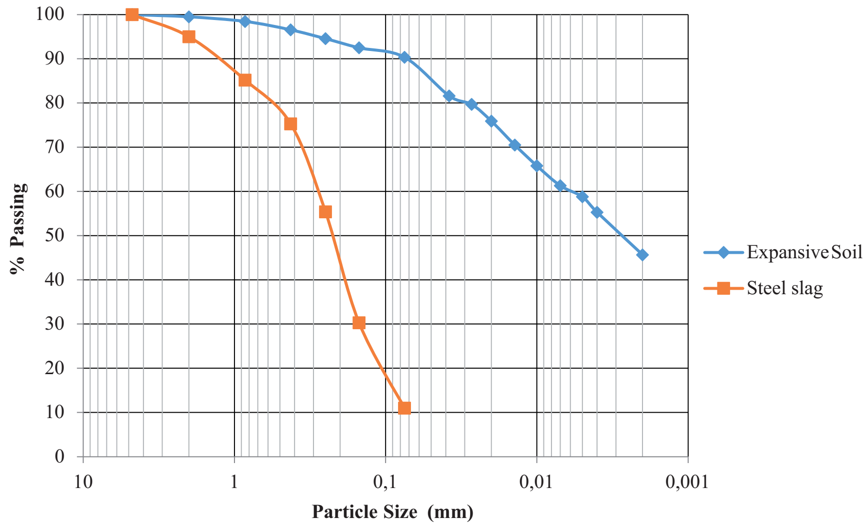

Fig. 1. Grain size distribution curve for crushed steel slag and natural expansive soil

Table 1. Physical characteristics and Atterberg limits of the considered soil

Soil Properties	Value	Unit
Natural moisture content	38.4	%
Liquid limit	90.8	%
Plastic limit	60.3	%
Plasticity index	30.5	%
Specific gravity	2.67	g/cm^3
Sand	10.8	%
Silt	39.5	%
Clay	49.7	%
UCS Soil classification	CH	–
Activity	0.55	–
Maximum dry density	1.504	g/cm^3
Optimum moisture content	19.77	%
Free Swell Index	104.6	%
UCS	94.2	kPa
CBR	3.6	%

According to the Unified Soil Classification System (USCS) (ASTM D 2487-10), steel slag is classified as SW (well graded sand). The steel slag sample had a specific gravity of 3.37.

2.2. Materials

2.2.1. Sample Preparation

ASTM [31] standard methods were used to collect soil samples and prepare them for testing. To obtain a uniform distribution, the soil sample used in this study was dried at 105 C^0 in a drying oven and then passed through sieve number 4 (4.75 mm in diameter). Steel slag samples were crushed into finer particles and sieved No. 40 (0.425 mm), after which they were stored in a plastic bag. Steel slag is added to soil samples in various percentages of 0, 5, 10, 15, 20, and 25% by weight.

2.2.2. Testing Program

A testing program was designed to investigate the behavior of natural and treated clay soil in order to meet the study's goals. Atterberg limits, free swell test, grainsize analysis, specific gravity, unconfined compressive strength, Standard Proctor Compaction, and California bearing ratio (CBR) were among the tests carried out. These tests were carried out with various percentages of steel slag added to the treated soil under optimum water content and maximum dry density conditions determined by the Proctor Compaction test.

- **Specific gravity**

Displacement in a water pycnometer (volumetric bottle) was used to determine the specific gravity of a natural and stabilized soil sample. The ASTM standard test method was used to determine the specific gravity of both expansive soil and steel slag. According to ASTM D 154-00, disturbed samples were tested by carefully placing 25g of oven-dried soil sample in a pycnometer half-filled with distilled water. Vacuum pumps were used to remove the air trapped in the soil sample for about ten minutes. After that, the bottle was filled to the calibration mark with distilled water and brought to a constant temperature. It was weighed in a balance after being carefully cleaned and dried.

- **Atterberg Limits**

The liquid limit (LL) and plastic limit (PL) tests were performed according to ASTM D 4318-10 after each soil-additive mixture was passed through sieve number 40 (0.425 mm in diameter). When a portion of soil is placed in a standard cup and then cut by a groove of standard dimensions, it flows together at the base of the groove for a distance of 13 mm when subjected to 25 shocks from the cup being dropped 10 mm in a standard Casagrande liquid limit apparatus operated at a rate of two shocks per second. The plastic limit (PL) is the water content in percent at which a soil can no longer be deformed without crumbling when rolled into 3.2 mm diameter threads.

- **Grainsize analysis**

The analysis of grain size in natural soil was done in two stages. Wet sieve analysis for course-grained soil was performed in the first stage using the ASTM D 422-63 test method. After washing with water, a 1000-gram weight of air-dried soil sample was sieved through a set of sieves stacked one above the other. The soil sample was washed, air-dried, and sieved at 0.075 mm before being dried in an oven at 110°C for 24 hours. After the sample had been dried, it was sieved so that the opening grew smaller from the top sieve down, with a pan at the bottom of the stock after the sample had been dried in the oven. For about ten minutes, the entire set of sieves was shaken horizontally until the weight of soil left on each sieve remained constant. The hydrometer test method was used to determine soil particles less than 0.075 mm (passing 200 mesh sieves) in the second stage. It is based on the natural process of soil particles settling in water due to gravity. Course soil suspension settles out more rapidly than the finer ones of the same specific gravity. Based on the ASTM test standard, a hydrometer analysis was performed to determine the silt and clay fractions. 50 gm of soil passed through sieve No. 200 was mixed with water and a dispersing agent (sodium hexametaphosphate) in a 1000 ml jar.

Readings were taken at intervals of 0.75, 1, 2, 4, 8, 15, 30, 60, 120, 240, and 1440 minutes, with the hydrometer remaining in the suspension the entire time and the thermometer recording the corresponding temperature of the suspension. All of the reading data was compiled and determined to different sieve sizes for the different hydrometer reading values after the twenty-four-hour reading. The combined wet sieve and hydrometer tests were then merged to determine the combined percent finer and these percent finer were plotted against particle sizes. The gradation of the tested soil is indicated by the shape of the plotted curve.

- **Standard Proctor Compaction test**

The relationship between dry density and moisture content for a given degree of compactive effort yields values of optimum moisture content (OMC) and maximum dry density (MDD) from laboratory compaction. In this experiment, soil samples were compacted in a standard mold with standard compaction energy using the standard Proctor test. The standard Proctor test employs a 105 mm diameter mold and 25 blows from a 2.5 kg hammer with a compaction energy of 593.7 kJ/m^3 to compact three separate layers of soil. American Society for Testing and Materials (ASTM) standard manual was used for the test methods. As a result, the soil was first air-dried before adding water to each sample to regulate the water content. The plastic strips prepared for this test were mixed into the soil. The soil mixed with plastic strips was then deposited and compacted in three layers in the Proctor compaction mold, with each layer receiving 25 standard hammer blows. The surface of the previous layers is scratched before each new layer is placed to guarantee uniform distribution of the compaction effects. After removing and drying the sample at the end of the test, the dry density and water content of the sample are determined for each Proctor test. Plastic strips did not break after the compaction. A compaction curve was plotted based on the entire set of results.

- **Free Swell Tests**

A free swell test provides a reasonable estimate of a soil's degree of expansiveness. The procedure for performing the free swell tests was based on the ASTM D 4546-08 standard's recommendation. Pouring 10 ml of dry soil through a 0.425 mm (No. 40) sieve into a 100-ml graduated jar filled with water was used to conduct the test. After 24 hours, an oven-dried sample was prepared and filled into a small tube with an initial volume of 10 ml, and then filled with water to fill the bottle up to the upper mark. After that, the soil's swelled volume was measured after the particles settled for 24 hours.

- **Unconfined Compressive Strength (UCS) Test**

The shear strength parameters of the samples with additives were evaluated using the unconfined compressive strength test method. The samples were molded into stainless steel tubes with a height of 76 mm and a diameter of 38 mm, and then compressed to achieve the desired compaction characteristics for each additive level. The samples were taken out of the tubes and tested at a rate of 1 mm/min on the spot. The ASTM D 2166-00 standards were used to conduct the unconfined compressive strength test.

- **California Bearing Ratio (CBR)**

A free swell test provides a reasonable estimate of a soil's degree of expansiveness. The procedure for performing the free swell tests was based on the ASTM D 4546-08 standard's recommendation. Pouring 10 ml of dry soil through a 0.425 mm (No. 40) sieve into a 100-ml graduated jar filled with water was used to conduct the test. After 24 hours, an oven-dried sample was prepared and filled into a small tube with an initial volume of 10 ml, and then filled with water to fill the bottle up to the upper mark. After that, the soil's swelled volume was measured after the particles settled for 24 hours.

3. Result and discussions

The test results are presented and discussed in this section. The results of each test performed to evaluate the effect of steel slag on the engineering properties of the soil were presented and discussions were held on each result. The relationships between each of the properties and the steel slag content are graphically presented.

3.1. Effect of steel slag on the Free swell value

A free swell test, conducted with a cylindrical tube without any surcharge load, measures the degree of swell for a particular soil. As shown in Figure 2, free swell for treated soil

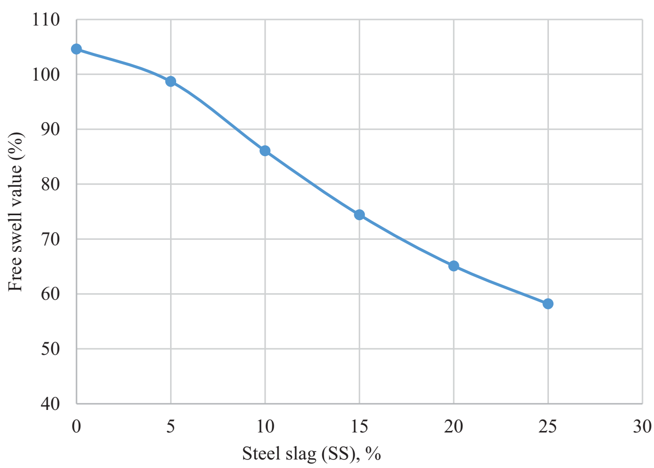

Fig. 2. Variation of Free swell value with Steel slag (SS)

slightly decreases as the amount of steel slag required to stabilize the soil increases. The reduction in the free swell index falls in the marginal range for the degree of expansiveness.

3.2. Effect of steel slag on the specific gravity

Figure 3 depicts the variation in specific gravity test results for both treated and untreated soil samples with steel slag. With an increase in steel slag content from 0–25%, the average specific gravity of the expansive soil increases from 2.67 to 3.05. The presence of a high amount of iron in slag, as well as a higher specific gravity than the expansive soil, accounts for the increase in specific gravity for treated soil.

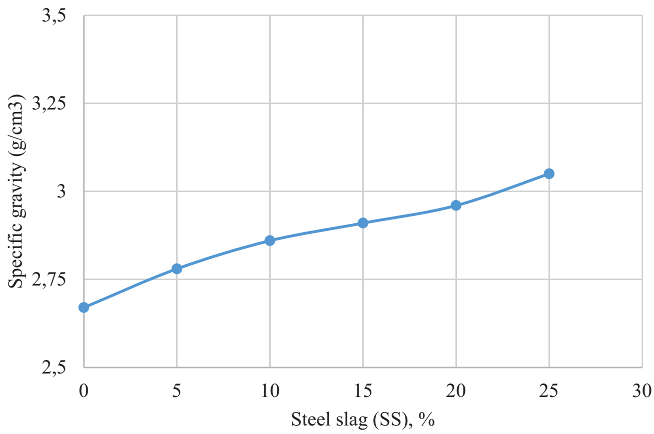

Fig. 3. Variation of Specific gravity with Steel slag (SS)

3.3. Effect of Steel slag (SS) on Consistency Limits

Figure 4 depicts the variation of Atterberg limits and linear shrinkage with the addition of steel slag. All of those limits were reduced with the addition of steel slag, as can be seen. This could be due to a decrease in the percentage of water absorbed by the soil. The decrease in the thickness of the double layer of clay particles resulted in lower liquid limit, plastic limit, and linear plasticity index values. A reduction in the LL and PI of the treated soil is expected due to the non-plastic nature of the steel slag particles. This is due to the cation exchange reaction, which results in an increase in the attraction force, causing the particles to flocculate. The particle size of the mixed sample increases when steel slag is combined with soil. The surface area of particles has decreased as particle size has increased. Furthermore, as the amount of steel slag in the soil mixture increases, the amount of clay minerals in the soil decreases. As a result, the soil mixture's water holding capacity decreased, lowering the liquid limit, plastic limit, and linear shrinkage limit.

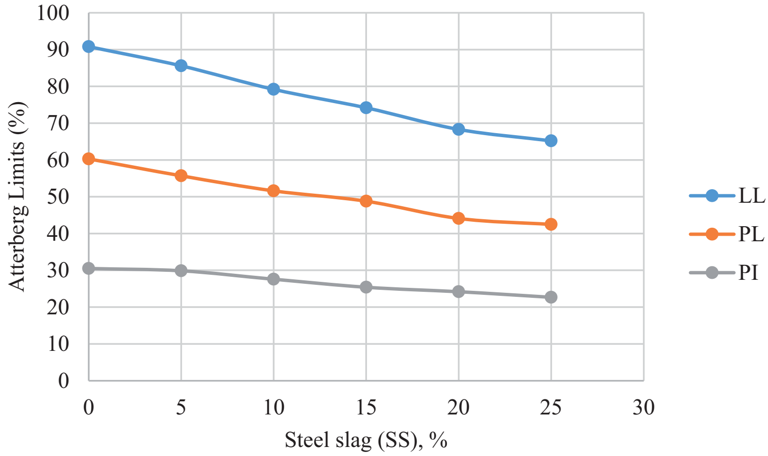

Fig. 4. Variation of Specific gravity with Steel slag (SS)

3.4. Effect of Steel Slag on Compaction Parameters

Fig. 5 and Fig. 6 show the variations in water content with dry density for soil samples containing various percentages of steel slag. The maximum dry density (MDD) and optimum moisture content (OMC) of natural soil were found to be 1.504 g/m^3 and 19.77%, respectively, for natural soil. With the addition of 25% steel slag to the expansive soil samples, the value of MDD was increased to 1.6918 g/m^3 and the value of OMC was decreased to 12.5%, as shown in Fig. 5. The increase in MDD value with increased steel slag content is due to the steel slag particles, which are heavy weight materials with a high specific gravity compared to natural soil samples. Due to its lower water adsorption, steel

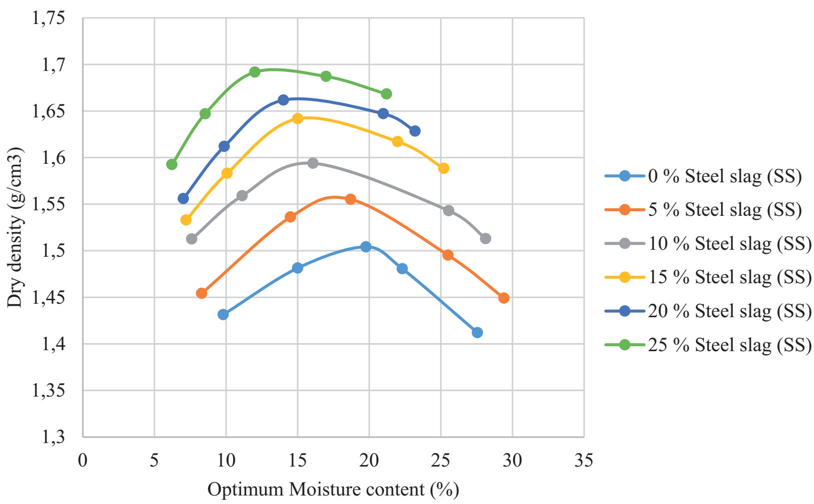

Fig. 5. Compaction curves of samples with the different content of steel slag

slag reduces the diffused double layer thickness and brings the particles closer together, increasing the MDD value. As a result, the particles pack together and the dry density rises with the same amount of compaction effort. The OMC values decreased as particles became closer together and their water holding capacity decreased.

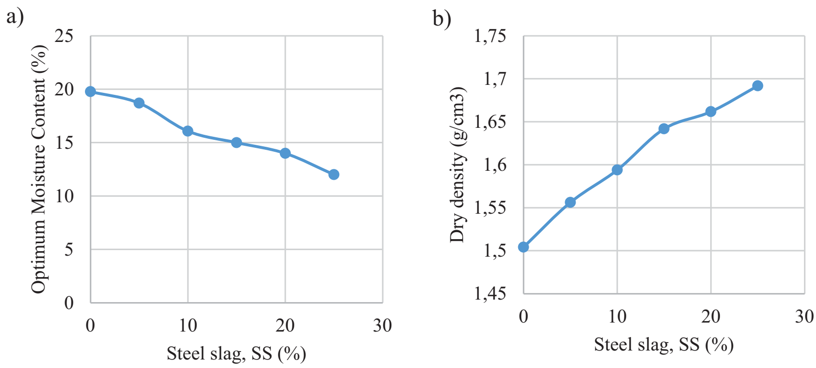

Fig. 6. Variation of the effect of steel slag on the (a) optimum moisture content (b) dry density

3.5. Effect of Steel Slag on Swelling Characteristics

Many factors, including clay mineral composition, amount of nonclay material present, density, void ratio, and cementation, have been shown to influence the decrease in the values of swelling pressure and swelling percent of an expansive soil. The presence of steel slag reduces the clay-mineral content per unit mass of the mixture, or the total surface area of expansive clay particles, resulting in a decrease in swelling characteristics. Figure 7

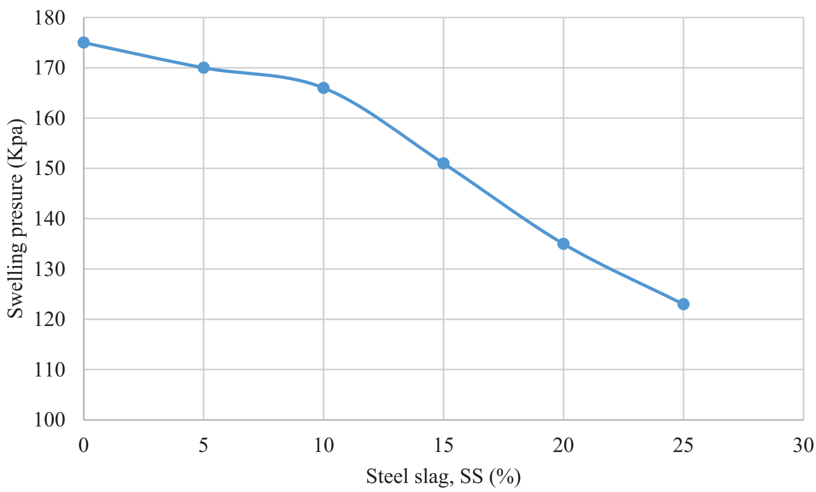

Fig. 7. Variation of Swelling pressure with Steel slag (SS)

shows that when 25% steel slag was added to the mix, the swelling pressure dropped from 175% to 123%. The non-plastic nature of steel slag aggregates causes a decrease in swell value and swell pressure as steel slag content increases.

3.6. Effect of Steel Slag on Swelling Characteristics

Figure 8 depicts the variation in unconfined compressive strength (UCS) of a steel slag-stabilized soil. The UCS values increase as the amount of steel slag increases, as shown in this graph. Table 2 shows how the strain changes when steel slag is added. Overall, the results show that the strength of the expansive soil stabilized with steel slag increases significantly up to the optimum content of steel slag, and then decreases as the steel slag content is increased. As a result, steel slag can be used to increase the strength of expansive soil.

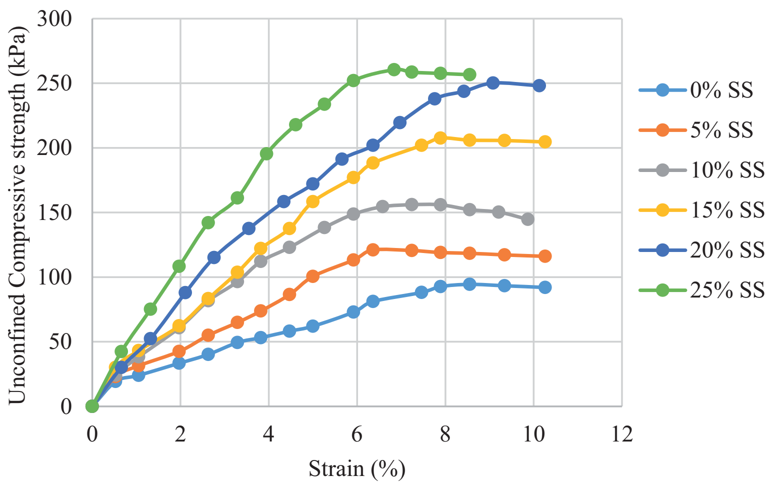

Fig. 8. Variation of Unconfined Compressive strength (kPa) and strain with steel slag (%)

Table 2. Effect of the steel slag on the unconfined compressive strength

Steel slag content (%)	0.0	5.0	10.0	15.0	20.0	25.0
UCS (kPa)	94.3	121.72	156.58	207.67	250.54	260.6
Strain (%)	6.23	4.51	3.94	3.32	2.91	2.54

3.7. Effect of steel slag (SS) on California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) is a penetration test that evaluates the mechanical strength of road subgrades and base courses in a comprehensive manner. The samples were prepared at the optimum moisture content, as determined by the modified Proctor compaction test, and soaked for seven days to determine the CBR value. Figure 9 shows that steel slag was effectively worked, resulting in significant increases in CBR value. As a result, using 25% SS resulted in a higher CBR value. This is because the raw iron content of the steel slag additive is high. Figure 9 also shows that when 25% steel slag was added to the expansive soil samples, the CBR values increased from 3.6% to 6.8%. The increased CBR value could be due to the iron material's role in the steel slag.

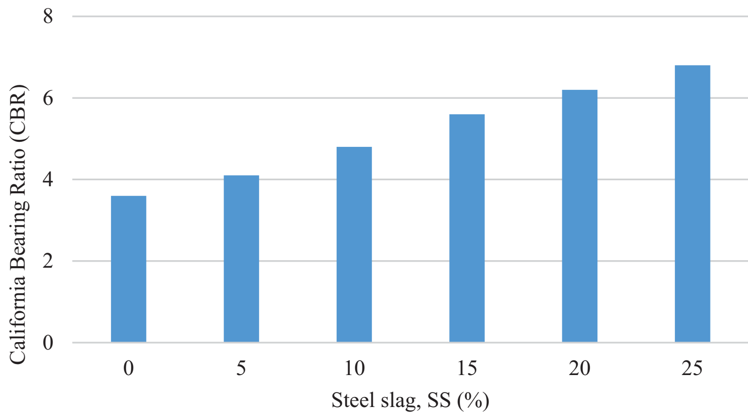

Fig. 9. Variation of CBR values with percentages of Steel Slag

4. Conclusions

This study focused on the effect of steel slag stabilizer on engineering properties, specifically the swelling and strength properties of a highly expansive soil. The soil used in the experiments has a free swell test of 104.6%, indicating that it is a highly expansive type. The type of soil is high expansive clay. The addition of steel slag to the expansive soil alters the soil's geotechnical properties significantly. As a result, the liquid limit drops from 90.8 to 65.2%, the plastic limit drops from 60.3 to 42.5%, and the plasticity index drops from 30.5 to 22.7% when 25% steel slag is added to expansive soil, according to the Atterberg limit test results. Specific gravity rises from 2.67 to 3.05 when 25% steel slag is present. The free swell value decreased from 104.6 to 58.2%. The maximum dry density increases from 1.504 to 1.69 g/cm^3 in the standard Proctor compaction test, while the optimum moisture content decreases from 19.77 to 12.01%. According to unconfined compressive strength tests, the addition of 25% steel slag to expansive soil increases the unconfined compressive strength of the soil from 94.3 to 260.6 kPa. The addition of 25% steel slag increases the California bearing ratio value from 3.64 to 6.82%, according to the California bearing ratio test. As a result, steel slag has been found to improve the geotechnical properties of expansive soil.

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