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Modeling the application of steel slag in stabilizing expansive soil

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Abstract
The objective of this study was to evaluate the suitability of steel slag as an additive to the engineering properties of weak clay soil. Different geotechnical laboratory tests were conducted on both stabilized and natural soils. Steel slag (SS) was added at a rate of 0, 5, 10, 15, 20, and 25% to the soil. Specific gravity, grain size analysis, Atterberg limit test, compaction test, free swell, California bearing ratio (CBR), and unconfined compression strength (UCS) are among the tests that were performed. 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 the expansive soil. With 25% steel slag content, the specific gravity increases from 2.67 to 3.05. The free swell value decreased from 104.6 to 58.2%. In the Standard Proctor compaction test, the maximum dry density rises from 1.504 to 1.692 g/cm^3, while optimum moisture content falls from 19.77 to 12.09%. From the UCS test, mixing 25% steel slag into the soil increases the unconfined compressive strength from 64.3 to 170.6 kPa. Additionally, the CBR value increases from 3.64 to 6.82% as 25% of steel slag is mixed with the soil. As a result, steel slag has been found to improve expansive soil properties for geotechnical applications.

Keywords Steel slag · Expansive soil stabilization · Geotechnical parameters

Introduction

The presence of montmorillonite clay minerals in expansive soils makes them problematic in nature. It has a high tendency to volume change upon a change in moisture content, which is known as swelling potential (Reddy et al. 2020). Civil engineering structures with problematic soils can be very dangerous due to their high compressibility and low compressive and shear strength, which can lead to structural collapse (Zheng et al. 2009; Puppala et al. 2011).

Several studies have tried to minimize the negative impact of expansive soil structures. They have used fly ash (Choudhary et al. 2014; Zorluer and Gucek 2014; Al-Malack et al. 2016), lime (Zha et al. 2007; Rouaiguia and Abd El Aal 2020), cement (Fattah et al. 2010), marble dust (Abdul Waheed et al. 2021; Abdelkader et al. 2021; (Amena and Kabeta 2022); Rouaiguia and Abd El Aal 2020), plastic strips (Amena and Kabeta 2022); Peddaiah et al. 2018; Rawat and Kumar 2016; Irshayyid and Fattah 2019; Kabeta 2022) bentonite mixed with sand (Fattah et al. 2021), geogrid reinforced columns (Al-Omari et al. 2016; Masood et al. 2021), ceramic waste (Al-Bared et al. 2018), tiles (Al-Bared et al. 2018; Al-Bared et al. 2018; Al-Bared et al. 2019a; Al-Bared et al. 2019b), granite waste (Zainuddin et al. 2019) and steel slag (Asi et al. 2007; Abdalqadir and Salih 2020; Abdalqadir et al. 2020; Aldeeky and Al Hattamleh 2017; Shen et al. 2009). Steel slag (SS) waste is one of the materials from steel factories used in the construction industry, such as in mortar road base material (Chen, Zhou, and Wu 2007; Nadeem and Pofale 2012), cement manufacturing (Shen et al. 2009), (Huang and Lin 2010) and soil improvement (Abdalqadir et al. 2020; Abdalqadir and Salih, 2020; Wang et al. 2020; Liang et al. 2013; Patel and Patel 2016; Wang et al. 2019).

On the other hand, steel production has a variety of environmental consequences, including air pollution, wastewater contaminants, hazardous waste, and solid waste. Steel slag is well known for polluting fertile soils, surface waters, and groundwater when exposed to natural weathering conditions. Hence, several studies have used steel slag by recycling in geotechnical soil stabilizations

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to improve weak soils (Yadu and Tripathi 2013), (Golakiya and Savani 2015; Patel and Patel 2016; Aldeeky and Al Hattamleh 2017). Steel slag is the most cost-effective material for improving weak subgrade soil (Akinwumi 2014; Patel and Patel 2016). The study by (Brand et al. 2020) investigates the potential use of steel slag for stabilizing clay soil. As a result, when 15% steel slag is mixed with soil, the unconfined compressive strength increases by 91%, implying that steel slag can be used effectively as a soil stabilization mixture. Another study (Aldeeky and Al Hattamleh 2017) investigates how fine steel aggregates can help improve the geotechnical properties of highly plastic soils. They mixed 0–25% dry-weight steel slag soil with weak soil and conducted various geotechnical laboratory tests. Their findings show that it has a positive impact on the soil's engineering properties and can be used as an admixture to improve the strength of poor subgrade soil. The study by (Abdalqadir et al. 2020) found that stabilizing Iraqi city soil with up to 20% steel slag reduced the values of Atterberg limits, optimum moisture content (OMC), swelling pressure, and swelling percent. Steel slag, on the other hand, increased the values of maximum dry density, unconfined compressive strength, and California bearing ratio in clayey soil samples.

The steel industry is considered essential for a country like Ethiopia, which aspires to undergo a rapid process of industrialization and economic transformation. Steel slag from this industry was affecting the surrounding environment, and there was a need to minimize this waste by recycling for sustainable development. The suitability of steel slag in stabilizing expansive soil found in Ethiopia, specifically in Jimma town, has not been studied yet to minimize the impact of this waste on the environment. Hence, this study proposes the applicability of steel slag waste to improve the geotechnical properties of expansive to minimize environmental impact and to provide an alternative material for weak soil stabilization in road subgrade construction.

Materials and methods

Materials used

Soil

In Jimma, Ethiopia, soil samples were collected at a depth of 1.5 m below the ground surface and kept in bags to maintain their natural moisture content. Based on the test results, the samples were classified as high plasticity (CH) clay by the Unified Soil Classification System (USCS). Figure 1 depicts the soil sample's particle size distribution, and the geotechnical properties of the soil are summarized in Table 1.

Table 1 Physical characteristics and Atterberg limits of the considered soil

Soil Properties	Value	Unit
Liquid limit	90	%
Plastic limit	60	%
Plasticity index	30	%
Specific gravity	2.67	g/cm^3
Sand	9	%
Silt	30	%
Clay	61	%
Soil classification by USCS	CH	–
Activity	0.55	–
MDD	1.504	g/cm^3
OMC	19.77	%
Free Swell	104.6	%
UCS	64.2	KPa
CBR	3.6	%

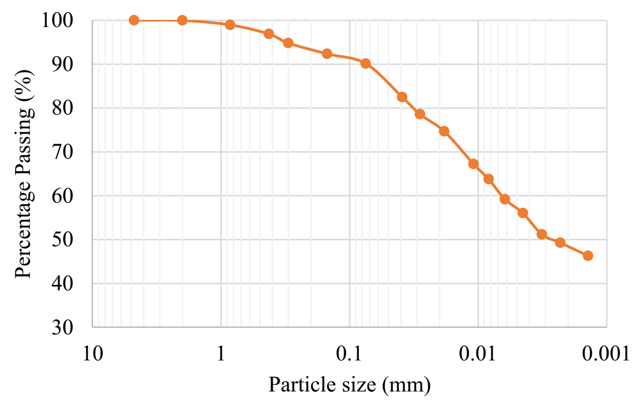

Fig. 1 Particle size distribution for expansive soil

Steel slag (SS)

The steel slag used in this study was produced in Ethiopia by the Ethiopian Steel Company. The grain size of this material is distributed according to Fig. 2. The Unified Soil Classification System (USCS) categorizes steel slag as well-graded sand. The steel slag sample had a specific gravity of 3.37.

Methodology

Preparation of sample

ASTM (Legget 1964) standard methods were used to collect soil samples and prepare them for testing. The soil sample

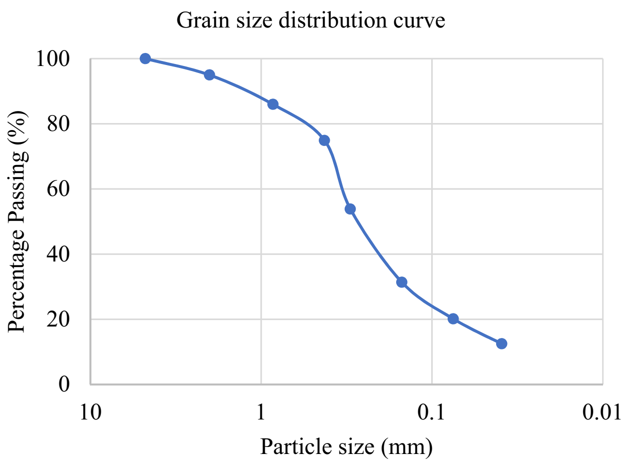

Fig. 2 Grain size distribution curve for steel slag

was dried at 110 °C in a drying oven and then sieved with sieve number 4 to achieve a uniform distribution. The samples of steel slag were crushed into smaller pieces and sieved using sieve No. 40. Steel slag was added to the soil samples in several percentages of 5, 10, 15, 20, and 25% of soil weight.

Testing program

The effect of steel slag on the geotechnical properties of weak expansive soil was investigated using a variety of laboratory testing programs. Atterberg limits, free swell test, grain size analysis, specific gravity, UCS, CBR, and Standard Proctor Compaction were among the tests carried out. These tests were conducted with various percentages of steel slag at optimum water content and maximum dry density, as determined by the Proctor Compaction test.

Specific gravity

Displacement in a water pycnometer (volumetric bottle) was used to determine the specific gravity of stabilized and natural soil samples. 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 25 g of oven-dried soil samples in a pycnometer. 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 the temperature was kept constant. It was weighed on a balance after being carefully cleaned and dried.

Atterberg limits

After passing each soil and steel slag mixture through sieve number 40, the Atterberg limit tests were performed according to ASTM D 4318-10. A small portion of the specimen paste is placed in a standard cup and, using a grove, it is prepared to standard dimensions. It flows together for a distance of 13 mm at the base after being subjected to 25 blows from the cup being dropped 10 mm in a standard Casagrande liquid limit apparatus. When rolled into 3.2 mm diameter threads, the plastic limit (PL) is the water content in the percent at which a soil can no longer be deformed without crumbling.

Grain size 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 g 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 oven dried at 110 °C for one day. After the sample had been dried, it was sieved so that the opening grew smaller from the top sieve down after the sample had been dried in the oven. For about ten minutes, the entire set of sieves was shaken horizontally until the density of soil left on each sieve remained constant. In the second stage, to determine soil particle size less than 0.075 mm (sieve No 200), the hydrometer test method was used. Soil suspensions with a coarser specific gravity settle out faster than those with a finer specific gravity. A hydrometer test was performed based on the ASTM test standard to determine the clay and silt fractions. 50 gm of soil passed through sieve No. 200 was mixed with water and dispersing agent in a 1000 ml jar.

The hydrometer data were taken at time intervals of 0.75, 1, 2, 4, 8, 15, 30, 60, 120, 240, and 1440 min. After the 24-hour, all recorded data was compiled, and the combined hydrometer test and wet sieve were then merged to determine the finer percentage, and a particle size curve was plotted. The gradation of the tested soil is indicated by the shape of the plotted curve.

Standard proctor compaction test

In this experiment, soil samples were compacted by standard compaction energy in a standard mold 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. The 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 steel slag prepared for this test was mixed into the soil. In the Proctor compaction mold, the soil mixed with steel slag was deposited and compacted in three layers, with each layer being compacted by 25 standard hammer blows. Then, after removing and drying the sample at the end of the test, the water content and dry density of the sample are determined for each Proctor test. Plastic strips did not break after 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 according to the ASTM D 4546-08 standard's recommendation. Pouring 10 ml of dry soil through a 0.425 mm sieve diameter into a 100-ml water-filled jar with water was used to conduct the test. After preparing an oven-dried sample and filling a small tube with an initial volume of 10 ml, the bottle was filled with water to the upper mark after 24 h. After that, the soil's swelling volume was measured after the particles settled for 24 h.

Unconfined compressive strength (UCS) test

This test was used to determine the shear strength parameters of the samples with additives. Hence, ASTM D 2166-00 standards were used to conduct the UCS test. The sample for the UCS test was prepared at MDD and OMC from the standard compaction test. To achieve the suggested compaction characteristics, the samples were compressed after being molded into steel tubes with a 38 mm diameter and a height of 76 mm. The samples were taken out of the tubes and tested at a rate of 1 mm/min on the spot.

California bearing ratio (CBR)

The CBR value is one of the most important parameters for determining the strength of the subbase, base course, and subgrade materials for use in highway structures. As per ASTM D-1883-99, the soaked CBR test was conducted with a surcharge load of 4.5 kg at 1.27 mm/sec penetration. The soil specimen for the CBR test was prepared at MDD and OMC from the compaction test. The mold size used for this test is 178 mm in height and 152 mm in diameter. The soil samples were placed in the container for soaking considering the worst conditions. Several computations have been done to calculate the CBR values of the soil from the test results. The Ethiopian Road Authority (ERA) manual was used to determine the suitability of the CBR value.

Results and discussion

The results of each test performed for both stabilized and natural soils to evaluate the suitability of steel slag in improving the geotechnical parameters of the soil were presented and discussions were held on each result.

Effect of steel slag on the free swell value

As shown in Fig. 3, as the percentage of steel slag required to improve the soil increases, the free swell of treated soil decreases slightly. The degree of the expansiveness of the free swell index has decreased from highly expansive to the marginal range. This behavior of steel slag in reducing the free swell value agrees with the study by (Aldeeky and Al Hattamleh 2017) in which the free swell value was reduced by 58.3%. The free swell value also decreased by 45% when 20% steel slag was mixed with soil (Abdalqadir and Salih 2020). Other studies (Shalabi et al. 2017; Aldeeky and Al Hattamleh 2017; Zumrawi and Babikir 2017) also agree with this reduction in free swell value as a significant amount of steel slag is mixed with expansive soil.

Effect of steel slag on the specific gravity

Figure 4 depicts the variation in specific gravity test results for both stabilized steel slag and natural soil samples. 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 soil, accounts for the increase in specific gravity for the treated soil. The result of this study can be supported by (Golakiya and Savani 2015), in which the steel slag improves the specific gravity of soil.

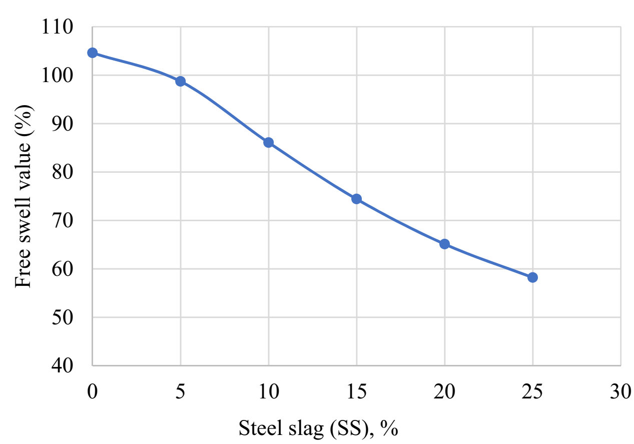

Fig. 3 Variation of free swell value on steel slag (SS)

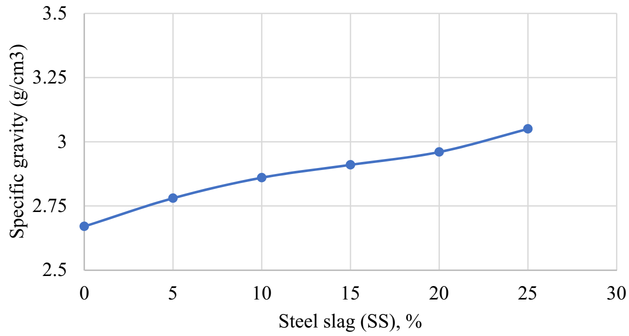

Fig. 4 Specific gravity variation with steel slag (SS)

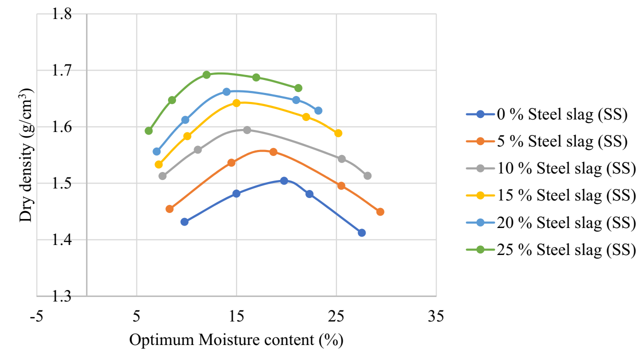

Fig. 6 Compaction curves of samples with different content of steel slag

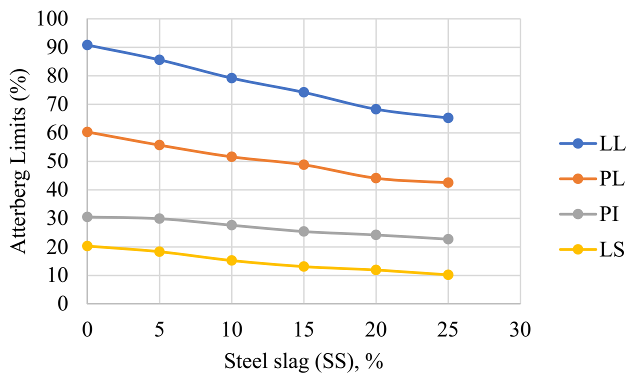

Fig. 5 Variation of Atterberg limit on steel slag (SS)

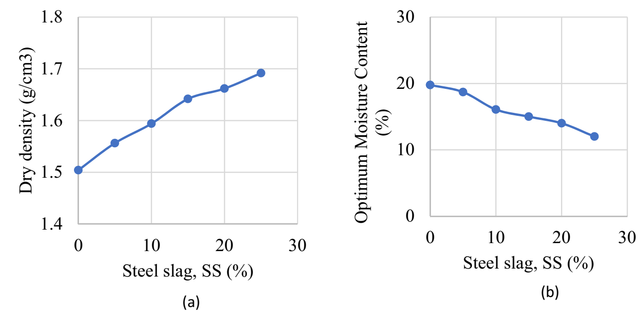

Fig. 7 Variation of steel slag effect on (**a**) dry density, and (**b**) optimum moisture content

Effect of steel slag (SS) on consistency limits

Figure 5 depicts the variation of Atterberg limits and linear shrinkage with the addition of steel slag. From the results, it can be observed that there is a significant reduction in Atterberg limits and linear shrinkage. This reduction is due to the fact that the addition of steel slag causes a reduction in the ability of water absorption. The decrease in the thickness of the double layer of clay particles resulted in lower Atterberg limits and linear shrinkage values. The reduction in the Atterberg limits of the stabilized soil is due to the non-plastic behavior of the steel slag particles and to the cation exchange reaction, which causes the particles to flocculate by increasing the attraction force. The particle size of the mixed sample increases when steel slag is combined with soil. As the particle size has increased, the surface area of the particles has decreased. 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-carrying capacity decreased, lowering the linear shrinkage and Atterberg limits.

Similar results have been found in other studies. (Aldeeky and Al Hattamleh 2017) discovered that with the addition of 25% steel slag, the LL and PI were reduced by 30% and 21%, respectively. The results of the study by (Abdalqadir and Salih 2020) show that adding steel slag to the expansive soil sample from 0 to 20% reduced the value of LL by 26%, the plasticity index by 12.64%, and the LS by 53.6%. Other studies, including (Abdalqadir et al. 2020; Zumrawi and Babikir, 2017; Shalabi et al. 2017; Patel and Patel 2016), also support these findings.

Effect of steel slag on compaction parameters

The variations in water content with dry density for soil samples containing various percentages of steel slag are shown in Figs. 6, 7. Natural soil has been found to have an MDD of 1.504 g/m^3 and an OMC of 19.77%. As shown in Fig. 6, the value of MDD was increased to 1.6618 g/m^3 and the value of OMC fell to 14% as 20% steel slag was added to the soil. Steel slag particles, which are heavy materials with a high specific gravity when compared to natural soil samples, cause an increase in maximum dry density as the steel slag content increases. Steel slag reduces the diffused double-layer thickness and the particles are brought closer together due to its lower water adsorption, resulting in a higher MDD value. As a result, the particles pack together and the MDD rises with the same amount of compaction effort. The OMC values decreased as the particles became closer together and their water-holding capacity decreased. Similar results have been obtained from the study (Aldeeky and Al Hattamleh 2017). They propose using fine steel slag to stabilize the weak subgrade soil, and adding up to 25% of steel slag increases the dry density by a significant amount. Another study (Abdalqadir et al. 2020) found that adding steel slag up to 20% to the soil increased dry unit weight from 18.34 kN/m^3 to 19.32 kN/m^3, while decreasing OMC from 15 to 11.28%. Other studies by (Hirapure and Dalvi 2018; Abdalqadir and Salih 2020; Patel and Patel 2016) also find similar results in CBR improvements with the addition of steel slag.

Effect of steel slag on swelling characteristics

Many factors, including the amount of nonclay material present, clay mineral composition, density, cementation, and void ratio, have an influence in reducing the values of swelling percent and swelling pressure of an expansive soil. Steel slag reduces the amount of clay minerals in the mixture as well as the total surface area of clay particles, resulting in a decrease in swelling characteristics. Figure 8 shows that when 25% steel slag was mixed into the soil sample, the swelling pressure dropped from 128–74%. Swell pressure and swell value decrease as the steel slag increases due to the non-plastic behavior of steel slag aggregates. Similar results were found in a study by (Abdalqadir et al. 2020), which found that by increasing the amount of steel slag by up to 20%, the swelling pressure dropped from 141.5 kPa to 74.2 kPa. The result of the study by (Patel and Patel 2016) also shows that the swelling potential of the clay, lateritic and black cotton clay soils is reduced as several percentages of steel slag are added to them.

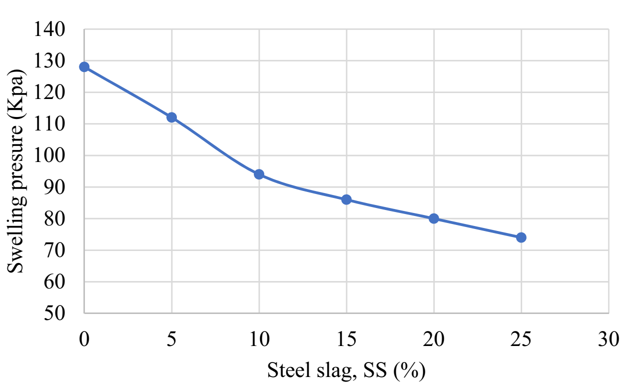

Fig. 8 Swelling pressure variation with steel slag (SS)

Unconfined compressive strength (UCS)

Figure 9 depicts the variation in the UCS value of steel slag-stabilized soil. As shown in this graph, the UCS values rise as the percentage of steel slag increases. It shows how the strain changes when steel slag is added. Overall, the results show that the unconfined compressive strength of soil stabilized with steel slag increases significantly until it reaches the optimum steel slag content, and then decreases as the steel slag amount increases. The results of this test are similar to those of (Abdalqadir and Salih 2020), in which the UCS rises from 649 kPa to 864 kPa as the steel slag content increases from 0 to 20%. Another study (Abdalqadir et al. 2020) also found that increasing the amount of steel slag by up to 20% increases the UCS values from 649 kPa to 864 kPa. As a result, steel slag can be used to increase the strength of expansive soil.

Steel slag effect on the California bearing ratio

The California Bearing Ratio (CBR) is a comprehensive penetration test for determining the strength of the soil. The CBR value was determined by soaking the samples for seven days at the optimum moisture content, as determined by the Proctor compaction test. Figure 10 shows that the steel slag was effectively worked, resulting in significant increases in CBR value. As a result, using 25% SS resulted in a greater CBR value. This is because the raw iron content of the steel slag additive is high. Figure 10 also shows that when 25% steel slag was mixed into the soil specimen, the CBR values increased from 3.6 to 6.8%. The increased CBR value could be as a result of the iron material's role in the steel slag. Several studies have confirmed that adding steel slag to weak expansive soil improves CBR values. According to the study by (Abdalqadir et al. 2020), the CBR value rises from 4.5 to 16% when steel slag is added to the soil sample from 0 to 20%. Another study by (Hirapure and Dalvi 2018) also finds similar results in CBR improvements with the addition of steel slag.

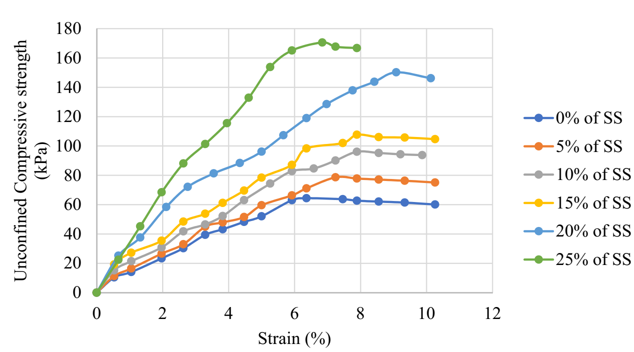

Fig. 9 Unconfined compressive strength (kPa) and strain variation with steel slag (%)

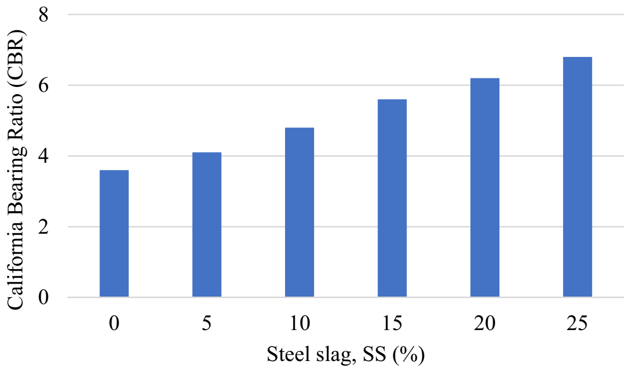

Fig. 10 Variation in CBR values as a function of steel slag percentage

Conclusions

This study attempted to determine the effect of steel slag on geotechnical properties, specifically on the swelling and strength of expansive soil. The soil used in the experiments has a free swell test of 104.6%, indicating that it is expansive in a high range. The type of soil is highly expansive clay. Steel slag changes the geotechnical properties of the expansive soil dramatically. 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 the 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 was reduced from 104.6 to 58.2%. The MDD rises from 1.504 to 1.69 g/cm^3 in the standard compaction test, while the OMC decreases from 19.77 to 12.01%. According to the unconfined compressive strength tests, the addition of 25% steel slag to soil increases the unconfined compressive strength of the soil from 94.3 to 170.6 kPa. According to the California Bearing Ratio test, a 25% addition of steel slag increases the California Bearing Ratio value from 3.64 to 6.82%. As a result, this study concludes that steel slag is a cost-effective material for improving soil geotechnical properties and a viable option for reducing the environmental impact of steel slag waste. This study lacks other advanced laboratory tests, such as chemical tests, due to the limited availability of laboratory tests, and recommends other researchers for future similar studies.

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