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Study on the Effect of Steel Slag in Improving Saline Soil

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Abstract: ***Saline soil is a special type of soil characterized by a high content of soluble salts and poor engineering properties. This study proposes the use of steel slag to improve saline soil and investigates the effects of different steel slag contents and curing ages on the mechanical properties of saline soil through unconfined compressive strength (UCS) tests, direct shear tests, and Atterberg limits tests. The results indicate that steel slag powder significantly enhances the mechanical properties of saline soil. UCS, stiffness, and cohesion increase with curing age, while they exhibit an initial increase followed by a decrease as the steel slag content rises. The optimal improvement effect is achieved at a steel slag content of 2.5% and a curing age of 28 days, with respective increases of 103.9%, 303.2%, and 162.4%. Additionally, the internal friction angle increases with steel slag content, with a maximum increment of 7.81°. The Atterberg limits test results show that steel slag powder increases the plastic limit of saline soil, whereas the liquid limit and plasticity index decrease with increasing steel slag content. In summary, steel slag exhibits excellent potential for improving the properties of saline soil.***

Keywords: Saline soil, Steel slag, Mechanical strength.

1. INTRODUCTION

Saline soil, a special type of soil containing excessive soluble salts, is widely distributed in arid and semi-arid regions across the world [1]. The high salt content of saline soils is their most distinctive feature, and the soluble salts in the soils mainly include chloride, sulphate and carbonate, etc. The presence of these salts significantly alters the physical and chemical properties of the soils. Salt-laden soils have unique engineering properties, such as solubility, salt swelling and corrosion [2]. The accumulation of salts also destabilises foundations, damages roadbeds and affects the service life of engineering structures. These engineering characteristics make engineering construction in saline soil areas face many challenges and require special treatment measures.

Traditional soil curing techniques, such as lime or cement [3-4], are often used to mitigate these problems. However, their application is often limited due to high costs and environmental concerns, such as carbon emissions generated during the cement production process [5].

Steel slag is a solid waste byproduct generated during the steelmaking process. According to the World Steel Association, China's crude steel production in 2023 reached 1,019.1 million tons, accounting for more than 50% of the global crude steel output. According to statistics, steel slag production is about 15-20 percent of crude steel. The accumulation of a large amount of steel slag occupies land resources, and steel slag may generate dust during the process of stacking and transport, which threatens the environment and human health. Therefore, the resource utilization of steel slag should be given high priority.

In recent years, steel slag has been demonstrated to be used for soil curing. S. et al. [8] used steel slag as a clay curing agent and increased the unconfined compressive strength by 67% and 91% and the dynamic modulus by 212% and 221% when 10% and 15% steel slag were used, respectively, relative to unmodified clay. Chunyang et al. [9] found that moisture content significantly affected the unconfined compressive strength of carbonised steel slag cured soils, where quartz-only carbonised steel slag cured soils exhibited excellent resistance to wet and dry cycling. Kaolinite and montmorillonite, on the other hand, weakened the resistance of carbonised steel slag cured soils to wet and dry cycling. Xuefei et al. [10] used a combination of alkali slag, steel slag and blast furnace slag instead of cement for curing marine soft clay, and the cured soft clay produced hydrocalcium silicate and other gelling substances, which effectively improved the strength of the soil body. Yu et al. [11] found that cement, lime and steel slag can reinforce loess to different degrees, of which the principle of steel slag reinforcement is to enhance the connection between particles and fill the pore space through the hydration reaction and carbonation. Liyan et al. [12] added steel slag to marine silt to improve its dynamic properties. The dynamic shear modulus increased with the increase of steel slag content and the damping ratio decreased with the increase of steel slag content. Yu et al. [13] used steel slag powder to improve the disintegration resistance of laterite. The time required for complete disintegration of the specimens was significantly increased with the increase in steel slag powder content.

In this study, the effect of steel slag on the improvement of engineering properties of saline soils was investigated. In the experiment, steel slag was mixed in saline soils to improve the properties of saline soils and was maintained for a maximum of 28 days. Then the effect of steel slag on the mechanical properties of saline soil was investigated by the unconfined compressive test and direct shear test, and the effect of steel slag on the liquid limit, plastic limit water content and plasticity index of saline soil was investigated by the liquid-plastic limit test. The results of the study can provide reference for the improvement of saline soil.

2. TEST MATERIALS AND RESEARCH PROGRAM

2.1 Test Materials

The object of the study is the saline soil in the western part of Jilin Province, China. The basic properties of the saline soil are shown in Table 1, and the various contents of soluble ions and the corresponding detection methods are shown in Table 2. The total amount of soluble salts is as high as 0.703 per cent, and the main anion is HCO_3^{2-}, and the main cation is Na^+, which is typical of soda saline soils. Figure 1 demonstrates the particle size distribution curves of steel slag and saline soil.

Table 1: Basic properties of saline soils

Liquid limit (%)	Plastic limit (%)	Plasticity index	Maximum dry density $(g/cm3)^3$	Optimum water content (%)	Sand % (2–0.075mm)	Silt % (0.075–0.005mm)	Clay % (<0.005mm)
41.2	15.6	25.6	1.73	17.3	13.66	60.34	26

Table 2: Soluble salts of the saline soil

Soluble salts of the saline soil (mmol/100g)								Total soluble salts of the saline soil(%)
K^+	Na^+	Ca^{2+}	Mg^{2+}	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	
0.5213	8.4124	0.1618	0.1011	0.168	5.248737	1.8992	1.4465	0.703

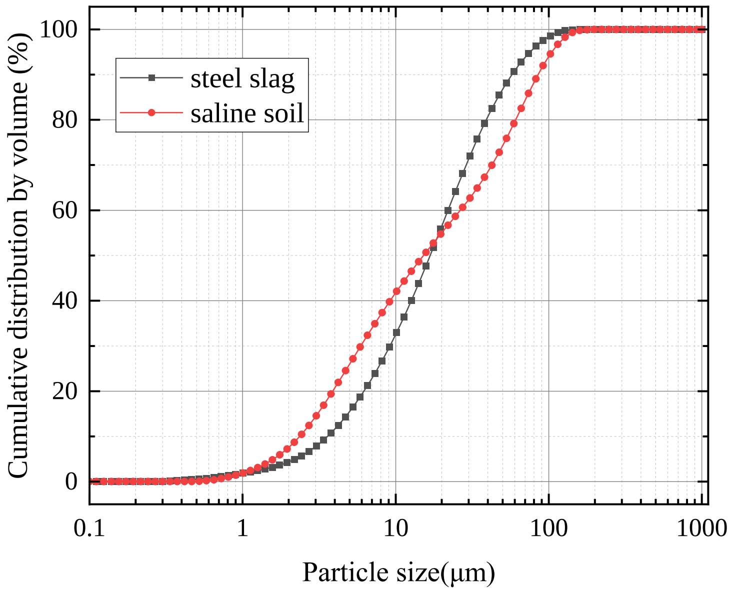

Figure 1: The distribution of different materials.

The steel slag used in this experiment was purchased from a steel mill in Hebei (Figure 2) and appeared powdery and grey-black in colour.

Figure 2: Steel slag.

2.2 Testing Methods

In order to investigate the effect of steel slag on the mechanical properties of saline soils, the saline soils were air-dried, crushed and passed through a 2 mm sieve with seven different steel slag contents, defined as the percentage of the mass of steel slag to the sum of the mass of the dry soil and the steel slag, such as 0.0%, 2.5%, 5.0%, 7.5%, 10.0%, 12.5%, and 15.0%. For configuration, the air-dried soil was first mixed with steel slag, after which it was sprayed with distilled water using a spray bottle and stirred until its moisture content reached the optimum moisture content. The configured soil was left sealed for 24 hours and after ensuring its uniform moisture content the soil was made into desired specimens. The two sizes of specimens were φ39.1mm*80mm and φ61.8mm*20mm cylindrical specimens, which were wrapped and sealed with cling film, and placed into a constant humidity and temperature environment for maintenance, with maintenance ages of 3, 7, 14, and 28 days, respectively. After reaching the curing age, the specimens were taken out for unconfined compressive test and direct shear test.

The soil samples after 28 days of conservation were air-dried, crushed and sieved through a 0.5 mm sieve, and then subjected to the Atterberg limits test.

3. RESULTS AND DISCUSSION

3.1 Unconfined Compressive Strength

Figure 3 shows the law of the effect of steel slag on the unconfined compressive strength of saline soil, from which it can be seen that the steel slag can significantly improve the unconfined compressive strength of saline soil. The effect of the content on the strength of the specimen is: with the increase of steel slag content, the unconfined compressive strength first increases and then decreases, and produces a maximum value at 2.5%. And the unconfined compressive strength of the specimen also increased significantly with the increase of the age of maintenance, the maximum value appeared at 2.5%, under the condition of 28 days of maintenance, the strength of 487.23kPa, compared with the strength of the unimproved saline soil 238.90kPa, which is an increase of 103.94%. The strength is increased because the hydration reaction of steel slag produces cementation inside the soil, but the increase in content weakens its strength. Overall, the unconfined compressive strengths of the improved soil samples were all improved compared to the pre-improved ones.

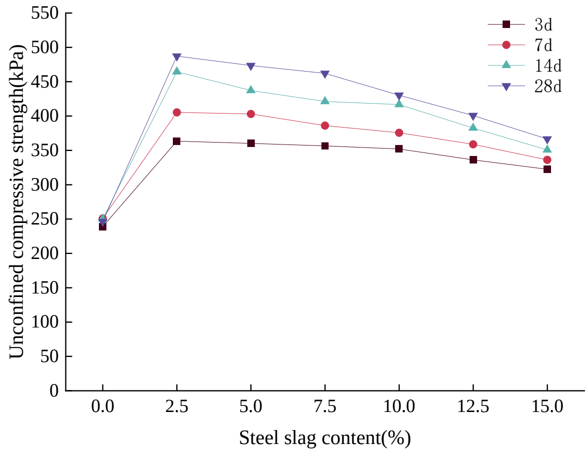

Figure 3: Unconfined compressive strength of soil specimens with different steel slag.

Figure 4 shows the effect of steel slag on the stiffness E_{50} of saline soils, which follows the same pattern as the unconfined compressive strength, increasing with the age of curing, with the content causing it to increase and then decrease, with the peak occurring at 2.5 per cent. The minimum E_{50} for saline soils was 237.7 kPa, which increased to 720.9 kPa when the steel slag content was 2.5 per cent and after curing.28 The E50s of the improved soils were all higher than those of the unimproved saline soils.

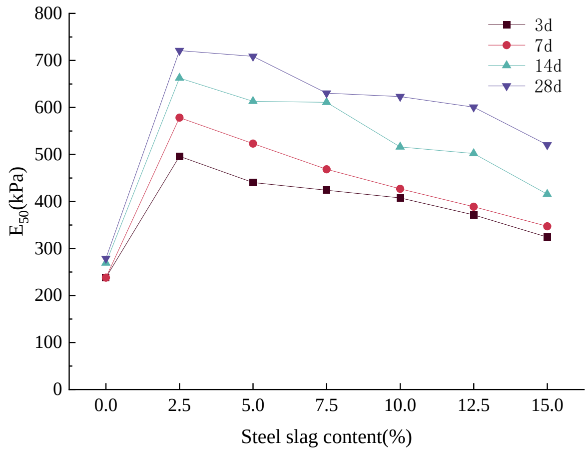

Figure 4: E_{50} of soil specimens with different steel slag contents.

3.2 Shear Strength

Figure 5 shows the effect of steel slag on the cohesion of saline soil, steel slag improved the cohesion of saline soil, the law of change is the same as the law of unconfined compressive strength: with the increase in the content of steel slag first increase and then decrease, the peak appeared in 2.5% appeared, and with the increase in the age of maintenance of the specimen cohesion also increased. The difference in cohesion between the specimens maintained for 3 days and 7 days was not significant, while the cohesion increased with the increase of the maintenance age to 14 days and 28 days, which showed that the cohesion increased more significantly with the longer maintenance period. The cohesion of the unamended saline soil was 87.1kPa and 89.6kPa, while the cohesion of the 2.5% content sample increased to 141.5kPa after 28 days of maintenance, which is a reflection of the connection between soil particles, and the stronger the connection, the greater the cohesion. It shows that the addition of steel slag improves the connectivity between soil particles, but the connectivity decreases when the added amount exceeds 2.5%.

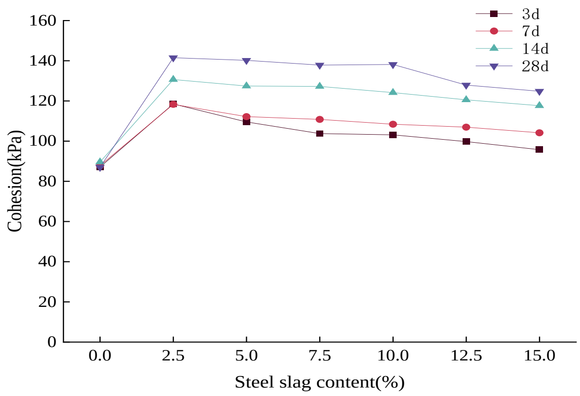

Figure 5: Cohesion of soil specimens with different steel slag contents

In Figure 6, the trend of the internal friction angle of the improved soil with the change of steel slag content is demonstrated. From the test results, it is obvious that the internal friction angle of the specimens shows a gradual increase with the increase of steel slag content, while the change of the age of maintenance does not have a significant effect on the internal friction angle. This suggests that the incorporation of steel slag plays a key role in the internal friction angle of the improved soil under the same maintenance conditions. Overall, the internal friction angle of the specimens increased significantly from 15.37° for unamended saline soil to a maximum value of 23.18°, an increase of 7.81°. This increase indicates that the incorporation of steel slag significantly enhanced the frictional resistance between soil particles, which effectively improved the shear strength of the improved soil.

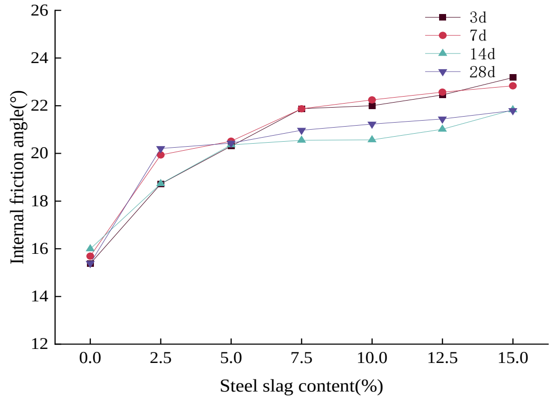

Figure 6: Internal friction angle of soil specimens with different steel slag contents

3.2 Atterberg Limits

Atterberg limits of saline soils with different steel slag content is shown in Figure 7. With the increase of steel slag content, the plastic limit of the soil samples increased slightly from 16.59% to 18.59% from unimproved, while the liquid limit showed a decreasing trend from 40.36% to 32.15%. The plasticity index decreased significantly, from 23.7 to 13.7.

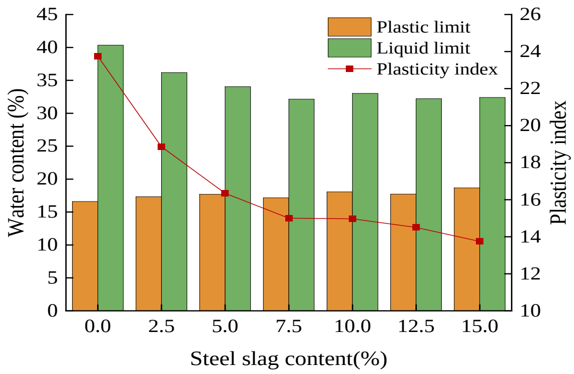

Figure 7: Atterberg limits of soil specimens with different steel slag contents

4. CONCLUSION

(1) Steel slag increases the unconfined compressive strength and stiffness of saline soil, which is shown to increase with the increase of the age of maintenance, and increase and then decrease with the increase of the content of steel slag, with the maximum value appearing in the condition of 2.5% steel slag content;

(2) Steel slag makes the cohesion and angle of internal friction of saline soil increase, in which the cohesion increases and then decreases with the increase of the content of steel slag, and the maximum value occurs under the condition of 2.5% content, and it gradually increases with the increase of the age of maintenance. The internal friction angle increases with the increase of steel slag content;

(3) The plastic limit of soil improved with steel slag increases, while the liquid limit and plasticity index decrease with increasing steel slag content.

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