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Application of Slag Compound as a Curing Agent for Dealing With Salt Expansion in Coastal Saline Soil

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Because of high concentration of soluble salt in coastal saline soil, it might cause salt expansion to some extent. In this paper, the application of slag compound as a curing agent (referred to as SM) for dealing with salt expansion in saline soil is investigated. This has done through studying the coefficient of salt expansion characteristics of the soil stabilized by slag compound. The test results approve that the SM improves saline soil's salt expansion and can make a soil characterized as expansible to the one with no salt expansion. Furthermore, SM decreases the coefficient of salt expansion after hydration by turning into crystal and gel formation, which improves the strength of soil samples and reduces the expansion of crystalline salts. On the other hand, SM reacts with the soluble salt in saline soil, which reduces the content of soluble salt and reduces the precipitation of crystalline salt and therefore lowers the coefficient of salt expansion. The study also compared the curing applications of SM, cement and quick lime. SM and cement have been found to have similar impacts on saline soil's salt expansion, whilst SM has been identified as a more economically viable option. Quick lime, however, is shown to have less curing application compared with both SM and cement. Thus, utilizing SM for improving saline soil's salt expansion has been proved to not only be technically feasible, but also economically viable.

1. Introduction

Salt expansion refers to the deformation caused by the loosening of soil particles because of the crystalline salt expansion in volume. In the process of the temperature change, the crystalline salt can absorb a large amount of water to make the crystalline salt expansion, destroy the original soil structure when the soluble salt crystallizes and precipitates (Zhang et al., 2015; Yang et al., 2016; Bao and Zhang, 2016). Although the coastal saline soil contains a part of the sulfate, the salt expansion is mainly caused by chlorine salt. The sulfate content is low in the coastal saline soil, so the salt expansion caused by sulfate is not obvious. While the chlorine salt content is higher, in the process of temperature from positive to negative, chlorine salt precipitates because of absorbing the water, and causes the expansion of saline soil volume. With the temperature changing seasonally, chlorine salt precipitates and dissolves repeatedly, the volume of saline soil expands and contracts repeatedly, which results the surface expansion in coastal saline soil area (Jian et al., 2016; Chai et al., 2013; Chai and Shi, 2012).
The temperature has an important effect on the salt expansion of saline soil. When the temperature drops below 0^{o}C, the salt expansion of the coastal saline soil is mainly caused by chloride salt and ice-salt (refers to $NaCl•2H_2O$), and their volume expansion is about 1.3 times, which results the expansion of saline soil. As the temperature decreases further, when the soil reaches freezing temperature, the water in the soil begins to freeze and the volume expands 1.09 times, which further aggravates the expansion of the soil. At present, the expansion after freezing is caused by the ice-salt and freezing water (Zhou et al., 2006; Fang et al., 2016).
The water also has an important effect on the salt expansion of saline soil. When the moisture content of saline soil is less, and the concentration of NaCl is greater than its solubility, the NaCl crystallizes and precipitates, and absorbs water to synthetize ice-salt, which exists in solid form. When the moisture content in saline soil is larger, and the concentration of NaCl is less than its solubility, the NaCl dissolves in water and exists in liquid form. When the moisture content in saline soil makes the NaCl's concentration equal to its

solubility, the NaCl is at the critical point from liquid form to solid form. Therefore, in a certain temperature condition, when the NaCl's concentration is greater than its solubility in saline soil, some NaCl absorbs water and becomes $NaCl•2H_2O$, the volume expands about 1.3 times, which results the volume expansion in coastal saline soil.

2. Test materials

2.1 Coastal saline soil

The investigated saline soil in this study through laboratory tests was supplied from Bohai region. Its physical properties are presented in Table 1.

Table 1: Physical properties of saline soil

Density (g/ml)	Natural moisture content (%)	Liquid limit (%)	Plastic limit (%)
1.79	29.68	33.72	17.41

The soluble salt component in the tested saline soil was as shown as Table 2.

Table 2: Analysis result of soluble salt component in saline soil

Ion concentration (mg/kg)							Total ion concentration (m/kg)	pH
K^+	Na^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}		
192	3690	475	346	172	6180	1670	12725	7.86

The average total salt content of the saline soil in this test was about 1.27% (refer to Table 2). Furthermore, the analysis result shows that the ratio between w(Cl^-) to w(SO_4^{2-}) is bigger than 2. Therefore, following the classification of saline soil, with the average total salt component in saline soil being between 1% to 5%, the samples categorized as medium saline soil.

2.2 Curing agent

The slag compound curing agent (hereinafter referred to as SM) in this study is used as a soil curing agent for coastal saline soil, and was invented by the author. It is predominantly composed by slag micro powder, construction plaster, quick lime and magnesia. The curing mechanism is as such that the curing agent can react with sodium ion, chloride ion and sulfate ion in saline soil and the hydration products include $3CaO•Al_2O_3•(0.5CaCl_2•0.5CaSO_4)•12H_2O$, $Ca_nSiO_{3.5}•xH_2O$(C-S-H), $0.8CaO•0.2Na_2O•Al_2O_3•3SiO_2•6H_2O$, $Mg_9(SiO_4)_4(OH)_2$(M-S-H) and $Ca_6Al_2(SO_4)_3(OH)_{12}•26H_2O$. All these together bring strength to the test specimen (Liu et al., 2014; Liu et al., 2014; Liu et al., 2015; Liu et al., 2014).

To investigate the application of SM for curing coastal saline soil's salt expansion issue, this study compared SM test results with the ones of cement and quick lime. The utilized cement was 32.5MPa composite cement and the quick lime was the one commonly used in construction.

3. Test results and analyses

3.1 SM results

Table 3: Optimum moisture content and maximum dry density

SM content	Plain saline soil (SM = 0)	3%	6%
Optimum moisture content (%)	15.42	15.56	15.82
Maximum dry density (g/cm^3)	1.88	1.92	1.95

To investigate the impact of SM on saline soil's salt expansion, plain saline soil (i.e. with no SM) and saline soil mixed with 3% and 6% SM were compared. The optimum moisture content and maximum dry density of these three soils combinations were obtained by heavy compaction test and the results are presented in Table 3.

Test operation process: The prepared soil samples are compacted according to the maximum dry density and the optimum moisture content, and packed in a cylindrical plexiglass test tube. The samples are placed at 20°C and maintained for 24 hours at the constant temperature. The upper and lower surface temperatures of the sample are both 25°C, and the control of the falling temperature is shown in Table 4:

Table 4: The upper and lower surface control temperatures of the sample

The falling temperature	one-level	two-level	three-level	four-level	five-level	six-level	seven-level	eight-level	nine-level	ten-level
The upper and lower surface temperatures (ºC)	20	15	10	5	0	-5	-10	-15	-20	-25
The upper and lower surface temperatures (ºC)	25	20	15	10	5	0	-5	-10	-15	-20

The falling temperature is divided into 10 levels. Firstly, the lower surface temperature keeps 25 ºC, the upper surface temperature is fallen into 20 ºC, the average falling rate is 0.5 ºC/h, then, the upper and lower surface temperatures are fallen by 5 ºC, and the rate is 0.5 ºC/h, and the falling temperature is carried out in turn. The coefficient of salt expansion during each stage of falling temperature can be calculated by Equation 1.

$$Y_i = \frac{\Delta H_i - \Delta H_{i-1}}{T_i - T_{i-1}} \tag{1}$$

Where Y_i is coefficient of salt expansion (%). ΔH_i-ΔH_{i-1} is the corresponding amount of salt expansion(mm). T_i is the next temperature (ºC) and T_{i-1} is the previous temperature(ºC).
The specific test results are shown in Figure 1.

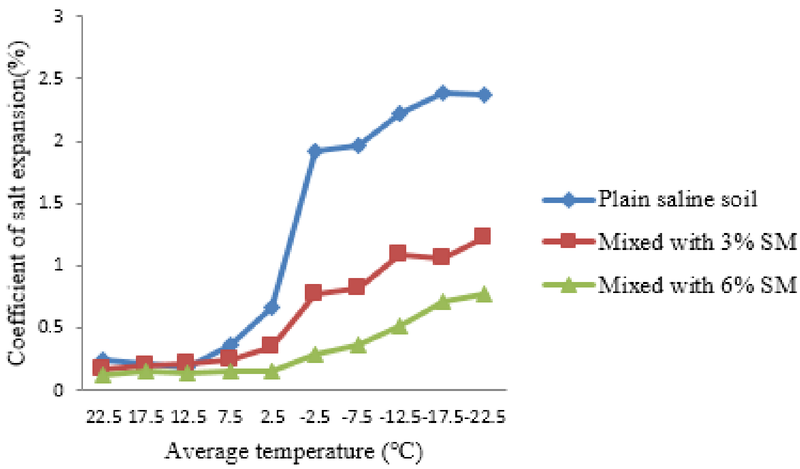

Figure 1: Comparison diagram of coefficient of salt expansion

Results presented in Figure 1 reveal that for plain saline soil, at the beginning of the test period, with the decrease of the specimen temperature, the phenomenon of salt expansion is not obvious. The main reason is that the sulfate content in coastal saline soil is low, and the salt expansion is mainly caused by sulfate at the beginning, so the salt expansion is not obvious. Then, as the temperature drops below 0ºC, the salt expansion is more severe. At this time, NaCl and NaCl•2H_2O cause the soil expansion. Because of the action of soluble salts, although the temperature has reached the freezing point of the water, the water in the saline soil has not frozen. As the temperature is further lowered, the water in the saline soil begins to freeze, and the water becomes into solid and the volume expands 1.09 times, which aggravates the soil expansion. When water is changed from liquid to solid, the concentration of NaCl will rise suddenly, and it will continue to crystallize, therefore, the phenomenon of salt expansion is outstanding. The expansion caused by the freezing soil consists of two parts, one is the salt expansion produced by the precipitation of NaCl, the other is the frost heave caused by freezing water.
For the saline soil mixed with 3% and 6% SM, at the beginning of the test period, due to the incorporation of slag compound curing agent for a short time, the SM is not fully hydrated, and the coefficient of salt expansion is not obviously improved. However, as the test time increases, the SM reacts with the chloride salt and sulfate in the saline soil. Because the SM hydration need to absorb the water in the saline soil, the chloride salt and sulfate concentration dissolved in water become larger, these will crystallize, which leads to salt

expansion. But, it can be seen from the Figure 1 that the salt expansion of the SM-soil is better than that of the plain soil. On the one hand, because the SM hydration produces strength, the solidified soil has the ability to resist salt expansion and reduce salt expansion. On the other hand, the SM reacts with the soluble salt, decreases the soluble salt content in saline soil, thereby which reduces the salt expansion.
The degree of salt expansion is shown in Table 5.

Table 5: The degree of salt expansion

Salt expansion category	Non salt expansion	Weak salt expansion	Medium salt expansion	Strong salt expansion
Coefficient of salt expansion (%)	Y<1	1<Y<3	3<Y<6	Y>6

The maximum salt expansion coefficient of the plain saline soil is 2.39, which belongs to weak salt expansion. The maximum salt expansion coefficient of the saline soil mixed with 3% SM is 1.22, which still belongs to weak salt expansion. However, the maximum salt expansion coefficient of saline soil mixed with 6% SM is 0.77, which belongs to non salt expansion. Therefore, the SM can improve the salt expansion of the saline soil.

3.2 Test results comparison and analysis

To comprehensively evaluate the application of SM, cement and quick lime as curing agents on saline soil's salt expansion, the test results for these three options are compared and shown in Table 6 and Figure 2.

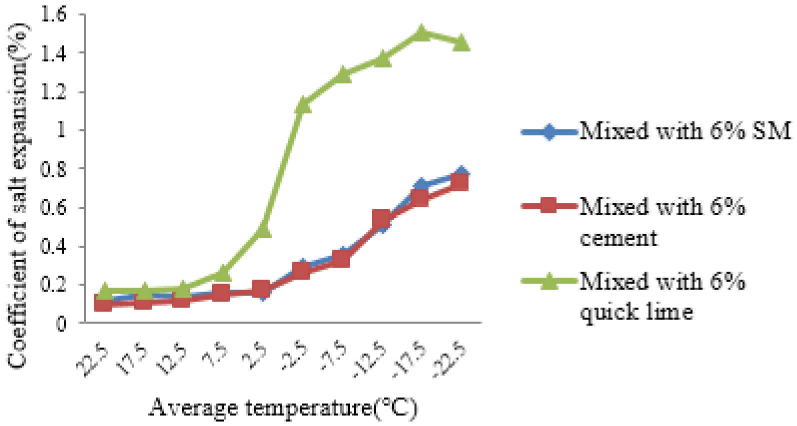

Figure 2: Comparison diagram of salt expansion coefficient for three different curing agent

Results presented in Table 6 reveal that, at the beginning of the test period, the salt expansion coefficient of cement-soil is lower than that of SM-soil. The reason is that the test blocks are placed for 24 hours before the test, cement hydration has been carried out, and produces strength, but the SM hydration is slower, then SM-soil's strength is low. However, the sulfate content in the coastal saline soil is low, the salt expansion is not obvious at this time. There isn't also obvious difference between the cement-soil and SM-soil in Figure 2. As the temperature decreases further, when the temperature changes from positive to negative, the salt expansion coefficient of SM-soil and cement-soil increases obviously because of the precipitation of $NaCl \cdot 2H_2O$ and ice, which results the soil expansion. At this time, the salt expansion coefficient of cement-soil and SM-soil is not obvious different in Figure 2. The reason is that the strength of SM-soil is low, the resistance to salt expansion is weak, but the SM reacts with the NaCl in the saline soil, which makes the less precipitated $NaCl \cdot 2H_2O$. The strength of cement-soil is higher, the resistance to salt expansion is stronger, but the precipitated $NaCl \cdot 2H_2O$ is more. So the SM-soil and cement-soil show similar coefficient of salt expansion.
The influence of quick lime on salt expansion of saline soil is obviously worse than that of SM-soil and cement-soil. At the beginning of the test period, the sulfate content in the coastal saline soil is low, the salt expansion is not obvious. As the temperature changes from positive to negative, A large amount of $NaCl \cdot 2H_2O$ and ice precipitate, which increases rapidly the salt expansion coefficient of lime-soil. The reason is that the strength of lime-soil is low, the resistance to salt expansion is weak, so the lime-soil still belongs to weak salt expansion.

From above analysis, SM and cement have better applications for improving saline soil's salt expansion compared to quick lime. When the combination amount is 6%, the coefficients of salt expansion of SM-soil and cement-soil are principally the same. Therefore, they have the same technical effects, but judging from economic aspect, SM has obvious advantage to cement. Thus adopting SM to improve saline soil's salt expansion is not only technically feasible but also economically viable.

Table 6: Coefficient of salt expansion results for three different curing agents

Ratio	Temperature (ºC)			Amount of salt expansion (mm)	Coefficient of salt expansion (%)
	Upper surface	lower surface	Average		
Mixed with 6% SM	20	25	22.5	0.62	0.12
	15	20	17.5	0.76	0.15
	10	15	12.5	0.68	0.14
	5	10	7.5	0.82	0.16
	0	5	2.5	0.78	0.16
	-5	0	-2.5	1.45	0.29
	-10	-5	-7.5	1.78	0.36
	-15	-10	-12.5	2.54	0.51
	-20	-15	-17.5	3.56	0.71
	-25	-20	-22.5	3.87	0.77
Mixed with 6% cement	20	25	22.5	0.48	0.10
	15	20	17.5	0.56	0.11
	10	15	12.5	0.62	0.12
	5	10	7.5	0.75	0.15
	0	5	2.5	0.83	0.17
	-5	0	-2.5	1.29	0.26
	-10	-5	-7.5	1.65	0.33
	-15	-10	-12.5	2.64	0.53
	-20	-15	-17.5	3.22	0.64
	-25	-20	-22.5	3.61	0.72
Mixed with 6% quick lime	20	25	22.5	0.87	0.17
	15	20	17.5	0.83	0.17
	10	15	12.5	0.92	0.18
	5	10	7.5	1.32	0.26
	0	5	2.5	2.45	0.49
	-5	0	-2.5	5.67	1.13
	-10	-5	-7.5	6.45	1.29
	-15	-10	-12.5	6.87	1.37
	-20	-15	-17.5	7.54	1.51
	-25	-20	-22.5	7.32	1.46

4. Conclusions

This paper has shown that SM reacts with soluble salt in saline soil, reduces the content of soluble salt, reduces the precipitation of crystalline salt, which reduces the coefficient of salt expansion. Furthermore, SM produces crystal and gel after hydration process, and those improve the test block's strength and restrict the expansion of the crystalline salt and ice, which also reduces the coefficient of salt expansion. The test results have indicated that the tested saline soil was improved from salt expansion soil to non salt expansion soil. This paper, therefore, has proved that SM can be one of the effective methods to improve saline soil's salt expansion.

SM has been demonstrated to have a better application as a curing agent for dealing with saline soil's salt expansion compared with quick lime, and is a more effective option. However, when compared with cement, with a similar combination amount of 6%, the salt expansion coefficients of both options are principally the same. SM and cement both are found to have the same technical effect, but SM has obvious advantage to cement as a cheaper option. This paper has shown that adopting SM to improve saline soil's salt expansion is both technically and economically viable.

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