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Application of slag compound as a curing agent for dealing with dissolve collapsibility characteristic in coastal saline soil

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High concentration of soluble salt in coastal saline soil can dissolve soil particles to some extent. In this paper, the application of slag compound as a curing agent (referred to as SM) for dealing with dissolve collapsibility in saline soil is investigated. This has done through studying dissolve collapsibility characteristic of the soil stabilized by slag compound. The test results approve that the SM improves saline soil's dissolve collapsibility and can make a soil characterized as collapsible to the one with no dissolve collapsibility. Furthermore, SM decreases dissolve collapsibility after hydration by turning into crystal and gel formation, which improves the strength of soil samples and reduces the associated deformation. On the other hand, SM reacts with the soluble salt in saline soil, which reduces saline soil's sensibility to water and the associated deformation and therefore lowers the dissolve collapsibility. 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 dissolve collapsibility, 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 dissolve collapsibility has been proved to not only be technically feasible, but also economically viable.

1. Introduction

Common soil consists of solid (i.e. soil particle), liquid (i.e. water), and gas (i.e. air), while saline soil in addition to those contains crystal salt, especially soluble salt, normally dissolved in water. When water evaporates, the soluble attaches to the soil particle, which extremely changes physical and mechanical properties of saline salt. Dissolve collapsibility of saline soil can occur under the soil's self-weight or external pressure (e.g. caused by traffic load) and deform due to immersion of fresh water. The described deformation of saline soil is called dissolve collapsibility deformation and is generally expressed by either dissolve collapsibility value or coefficient of dissolve collapsibility. The dissolve collapsibility value is the difference of deformation value between test specimen immersed in water and test specimen under pressure only. The coefficient of dissolve collapsibility is the ratio between dissolve collapsibility and original test specimen's height.
The dissolve collapsibility of saline soil happens when the porosity ratio of soil is increased by dissolved soluble salt and salt crystal, and therefore the saline soil deforms under load (Jiang et al., 2016; Bao and Zhang, 2016). The saline soil has two kinds of dissolve collapsibility, namely dissolve collapsibility deformation and suffusion collapsibility deformation. Dissolve collapsibility deformation occurs when the saline soil is in contact with relatively small volume of water for a short time, i.e. during short immerse time when the water volume is small, during which part or all the crystal salt in saline soil dissolves in water. These damage the soil structure of saline soil by decreasing the soil strength. While in suffusion collapsibility, the soil is immersed in water for a long time with relatively high-water volume, during which seepage occurs. Under this condition, the crystal salt in saline soil is dissolved as saline solution by seepage and is taken away continuously, as the water is continuously replenished. The suffusion collapsibility erodes the soil particle which consists of crystal salt, fine soil particle and gel. The phenomenon leads to increased porosity in saline soil and as a result, under certain load, the soil structure can be damaged, causing severe suffusion collapsibility deformation (Wu et al.,

2016). The severity of dissolve collapsibility depends on various parameters including water volume, immersion time, salt variety and content, soil classification and structure, as well as seepage speed (Jiang et al., 2016; Bao and Zhang, 2016).
In coastal saline soil area, when building foundations and road subgrade encounter water, the soluble salt may dissolve, which may significantly decrease the structure strength and cause major settlements. This may severely damage a building, disturb transportation network and reduce assets' service life (Feng et al., 2010; Benarab et al., 2016).
Currently, soil-curing technology has been fully researched and applied in Japan, USA, Canada, Australia, South Africa and Europe. Although these curing agents are designated variedly, such as stabilizer, Fuji soil and so on, they can cure all sorts of soil materials. For instance, the state of Texas in the USA employs curing technique to cure highway subgrade of saline soil (Kitazume, 2007). The Central International Airport of Japan is built on an offshore artificial island based on solidified reclamation sludge (Xing et al., 2009). Most of the research on curing agents is still at an experimental stage to seek novel curing agents and curing methods, such as high-strength and anti-water erosion soil (HAS) and keda (KD)curing agents (Zhou et al., 2006; Liu et al., 2011; Cheng et al., 2011; Pang et al., 2009; Chai et al., 2007; Wang et al., 2010). These curing agents are prepared, based on salt species and content of soil, to study their adaptability to specific saline soils, and certain curing goals have been achieved. But, using cement, lime or existing curing agent to cure saline soil often leads to low strength and poor water stability. The main reason is the role of soluble salt in 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 sample is 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 sodion, chorion and sulfate ion in saline soil and the hydration products include $3CaO{\bullet}Al_2O_3{\bullet}(0.5CaCl_2{\bullet}0.5CaSO_4){\bullet}12H_2O$, $Ca_nSiO_{3.5}{\bullet}xH_2O$(C-S-H), $0.8CaO{\bullet}0.2Na_2O{\bullet}Al_2O_3{\bullet}3SiO_2{\bullet}6H_2O$, $Mg_9(SiO_4)_4(OH)_2$(M-S-H) and $Ca_6Al_2(SO_4)_3(OH)_{12}{\bullet}26H_2O$. 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 dissolve collapsibility issue, this study compared SM test results with the ones of cement and quick lime. The utilized cement was32.5MPa composite cement and the quick lime was the one commonly used in construction.

3. Test results and analyses

3.1 SM results

In engineering, coefficient of dissolve collapsibility (δ)is often used as an index for evaluating the dissolve collapsibility of saline soil. According to the associated codes (Geng and Yang, 2009), when δ<0.01, the saline soil is categorized as having no dissolve collapsibility, otherwise, it would be classified as collapsible saline soil. There are three methods for measuring coefficient of dissolve collapsibility, namely: indoor compression test, liquid discharging method and on-site immersion-load test. The indoor compression test is suitable for measuring the dissolve collapsibility coefficient for saline soil with regular shape. For saline soil without regular shape, however, liquid discharging method should be used, where the on-site immersion load test is not applicable.

Coastal saline soil is mainly silty clay and it can form regular shape after compaction. Therefore, indoor compression test was utilized to measure the coefficient of dissolve collapsibility. The coefficient within known pressure range can be calculated by Equation 1.

$$\delta = \frac{h - h_1}{h_0} \quad (1)$$

Where δ is coefficient of dissolve collapsibility (%). h is height of test specimen under certain pressure(mm). h_1 is height of test specimen after dissolve collapsibility under known pressure(mm) and h_0 is original height of test specimen(mm).

To investigate the impact of SM on saline soil's dissolve collapsibility, 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.

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

Specimen preparation: for plain saline soil, the air-dried saline soil was adequately mixed with non-ionic water and sealed for 24 hours. After the saline soil was fully mixed with water, compaction test apparatus was utilized to achieve required compactness for the soil specimen. After compaction, soil sampler was used to take out the soil sample and then a cutting ring, 79.8mm diameter and the height of 20mm, was utilized to take the specimen. To do the latter, the cutting ring's blade was made downward and pressed until soil specimen extended the ring. Surplus soil was then removed and the soil specimen was trowelled. For mixing saline soil with SM, considering the hydration reaction of curing agent, the soil sample had to be compacted immediately after preparation, whilst the sampling method was the same as plain saline soil. Considering the water's influence on saline soil's dissolve collapsibility, the prepared specimen was wrapped by plastics film to prevent water evaporation. The curing period was7 days.

The coefficient of dissolve collapsibility can be measured by single line or double line collapsibility tests. The single line test needs 5 soil specimens and its field sampling and indoor test are very complicated. At the same time, saline soil is easily influenced by external environmental factors, so it is very difficult to obtain required numbers of identical samples by cutting ring. While double line test needs only two specimens, and it is easier to make two identical soil specimens. However, the test time of double line test is longer, and therefore, the salt in saline soil can fully dissolve during test period (Geng and Yang, 2009). This research has adopted double line test because it was more convenient for specimen sampling and operation, as it is less labour intensive and it better simulated the actual project conditions. Double line triaxial medium pressure consolidation apparatus was utilized in this research. The prepared soil specimens were tested, by gradually loading one set of soil specimens till the deformation was stable under certain pressure, while the other set of soil specimens were immersed (using deionized water to immerse specimen from the bottom to up, the water was replaced continuously to make salt fully dissolve). Then pressure was increased until the deformation was stable again. The test pressure values include 50, 100, 200, 300, 400, 500 and 600KPa. During the test, the pressure shall be increased after the settlement under former pressure is stable, i.e. the deformation per hour doesn't exceed 0.01mm in two continued hours (Zhang and Yang, 2009).

The compression test was done on the consolidation apparatus according to existing national code *Standard for Soil Test Method GB/T50123*. The coefficients of dissolve collapsibility were calculated, see Figure 1, using the dissolve collapsibility test results on plain saline soil specimen and saline soil specimen mixed with 3% and 6% SM after 7 days' settlement under different pressure.

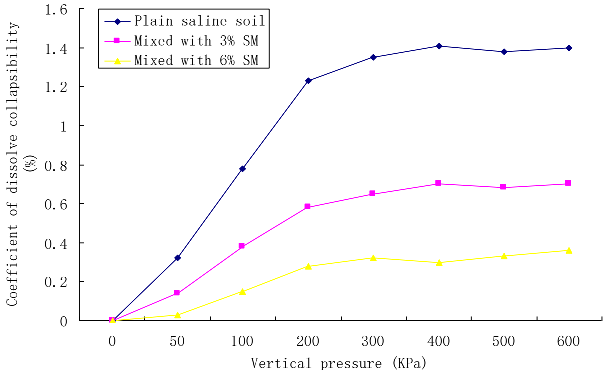

Figure 1: Comparison diagram of coefficient of dissolve collapsibility

Results presented in Figure 1 reveal that for plain saline soil, when the specimen is under pressure within 300KPa, as the pressure increases the coefficient of dissolve collapsibility is increased rapidly, while when the pressure is higher than 300KPa, the coefficient of dissolve collapsibility tends to be stable during pressure increase. Therefore, the coefficient of dissolve collapsibility under pressure range of 50KPato 300KPa was taken as the basis for judgment, which corresponds with 1.35% plain saline soil's coefficient of dissolve collapsibility, which is higher than the 1% threshold. Although, this plain saline soil specimen was made based on optimum moisture content and maximum dry density, following *Technical Code of Building on Saline Soil Regions GB/T 50942-2014*, it still had some dissolve collapsibility. The main reason was that the salt crystals in saline soil exist in porosity and in contact with soil particles and the salt crystals when combined with soil particles form the saline soil's skeleton. In low pressure, a short time is needed to reach stable settlement, whilst the immersion time is also short, therefore, salt, especially soluble salt, cannot dissolve adequately. During this process, the damage of water to soil's structure is small and as the salt crystal, now forming part of soil skeleton, has not been totally damaged the coefficient of dissolve collapsibility is small. When the pressure is increased and immersion time is elongated, the salt crystals begin to dissolve in a larger quantity and the soil structure is damaged relatively quickly. When the pressure reaches 300KPa, most of salt crystals in soil have been dissolved and soil structure has been thoroughly damaged and the salt crystals as soil skeleton have been dissolved in abundance. Thereafter, soil particles will be rearranged under pressure effect and the dissolve collapsibility will be increased quickly. At this stage, the coefficient of dissolve collapsibility reaches the highest. This with decreased soil void ratio, decreases the dissolved value of salt crystals, and as a result even with continuously increased pressure, the coefficient of dissolve collapsibility tends to remain stable.

For the saline soil mixed with 3% and 6% SM, when the vertical pressure is above 200KPa, the coefficient of dissolve collapsibility tends to remain stable. Thus, the coefficient of dissolve collapsibility under pressure range of 50KPa to 200KPa was taken as the basis for judgment. The coefficient of dissolve collapsibility of saline soil with 3%SM is 0.58%, which is less than the 1% threshold, and therefore is classified as having no dissolve collapsibility. The coefficient of dissolve collapsibility for saline soil with 6% SM is 0.28% which also has no dissolve collapsibility. The reason is the reaction between SM and soluble salt in saline soil, which reduces the crystal content. Nonetheless, the SM amount is not enough to react with all the soluble salt in saline soil. Therefore, when the specimen is under less than 200KPa pressure, the salt crystals dissolve gradually causing rearrangement of soil particles and therefore increasing its coefficient of dissolve collapsibility. When the pressure exceeds 200KPa, the influence of dissolved value on salt crystals to soil structure is decreased. This together with crystals produced by SM hydration results in the coefficient of dissolve collapsibility tends to remain stable even when the pressure is continuously increased. Increasing the amount of SM in the mixture will reduce the dissolve collapsibility of saline soil.

Judging from aforementioned analysis, the SM improves saline soil's dissolve collapsibility and alters the plain saline soil from collapsible soil to non-collapsible soil. SM turns into crystal and gel after hydration, which improves the test block's strength and reduces the deformation, therefore decreases the dissolve collapsibility. On the other hand, SM reacts with the soluble salt in saline soil, which reduces saline soil's sensibility to water, reducing the deformation and lowering the dissolve collapsibility.

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 dissolve collapsibility, the test results for these three options were compared and shown in Figure 2.

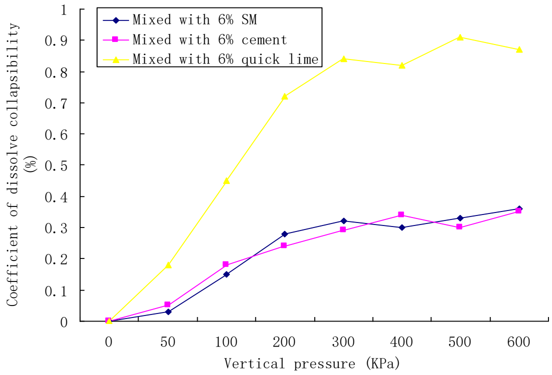

Figure 2: Comparison diagram of dissolve collapsibility coefficient for three different curing agents

It is evident from Figure 2that when the combination quantity remains the same, the coefficient of dissolve collapsibility is principally the same. Having said that, when the combination quantity is small, the strength of SM cured soil is lower than cement cured soil, whilst SM can react with the soluble salt in saline soil, to reduce the soluble salt in cured soil. During the dissolve collapsibility test, the dissolved soluble salt in cement soil is more than SM cured soil, so the porosity of cement soil is higher than SM cured soil. Although the cement soil has initial higher strength, its strength deduction after immersion is more due to porosity. Having said that, in the end, the dissolve collapsibility deformation of cement soil and SM cured soil are the same. This explains why these two types of curing agent have similar coefficient of dissolve collapsibility.

As for quick lime soil, the coefficient of dissolve collapsibility is noticeably higher than SM and cement cured soil. The mechanism of quick lime curing is mainly due to produced $Ca(OH)_2$by quick lime hydration, which is separated from solution and forms crystals. The $Ca(OH)_2$ can react with active SiO_2 and Al_2O_3 in soil and forms hydrated calcium silicate and hydrated calcium aluminate. But the $Ca(OH)_2$ crystal produced by this reaction has low strength and the hydration process between $Ca(OH)_2$ and SiO_2 and Al_2O_3 in soil is slow. In the dissolve collapsibility test after 7 days standard curing, the quick lime soil has low strength and low resistance to deformation, whilst, the quick lime cured soil still has plenty of soluble salt. During immersion, the soluble salt dissolves and increases the porosity of quick lime soil. Thus, when the vertical pressure is increased from 50KPa to 300KPa, the coefficient of dissolve collapsibility of quick lime soil has large growth and the final maximal coefficient is 0.84%. Although this coefficient of dissolve collapsibility is less than 1%, showing that quick lime cured soil has also no dissolve collapsibility. Figure 2 shows that the improvements of SM and cement on saline soil's dissolve collapsibility are much bigger than the quick lime.

From above analysis, SM and cement have better applications for improving saline soil's dissolve collapsibility compared to quick lime. When the combination amount is 6%, the coefficients of dissolve collapsibility of SM and cement 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 dissolve collapsibility is not only technically feasible but also economically viable.

4.Conclusions

This paper has shown that SM reacts with soluble salt in saline soil and reduces saline soil's sensibility to water immersion, associated deformation and the dissolve collapsibility. Furthermore, SM produces crystal and gel after hydration process, and those improve the test block's strength and reduce the deformation, so the dissolve collapsibility is further lowered. The test results have indicated that the tested saline soil was improved from collapsible soil to non-collapsible soil. This paper, therefore, has proved that SM can be one of the effective methods to improve saline soil's dissolve collapsibility.

SM has been demonstrated to have a better application as a curing agent for dealing with saline soil's dissolve collapsibility compared with quick lime, and is a more effective option. However, when compared with cement, with a similar combination amount of 6%, the dissolve collapsibility 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 dissolve collapsibility is both technically and economically viable.

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