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CONSTRUCTION ON PERMAFROST

THE INFLUENCES OF FREEZE-THAW CYCLES ON THE SHEAR STRENGTH OF EXPANSIVE SOIL TREATED WITH IONIC SOIL STABILIZER

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A study of the shear strength of expansive soil treated with ionic soil stabilizer during freeze-thaw cycles is presented. The shear strength of treated expansive soil is greater than that of untreated expansive soil at room temperature, and it is evident that the moisture content plays a leading role in this result. After a freeze-thaw cycle the shear strength changes little for untreated soil, but decreases gradually after ionic soil stabilizer treatment. Shear strength reaches the lowest values after seven freeze-thaw cycles. Finally, the influence of freeze-thaw cycles on the porosity of expansive soil is analyzed using scanning electron microscopy, which shows that the porosity of both treated and untreated soil increases with the number of freeze-thaw cycles, although porosity of the treated sample changes little.

Introduction

Expansive soil, which is mainly composed of highly dispersed and plastic clay particles, is highly sensitive to thermal environmental changes [1-3]. Such soil swells and softens when hydrated, but shrinks and cracks after water loss, potentially causing harm to engineered structures [2-4]. Ionic soil stabilizer (ISS) is an ionic chemical solution that is applied as a treatment to various soils with a clay content >25%. ISS has been widely used in road and water conservancy projects [5-8]. According to various engineering tests, a predetermined concentration of ISS solution has been shown to significantly reduce deformation of expansive soil under normal conditions and improve its compressive strength [9, 10]. However, freeze-thaw cycles also strongly influence expansive soils [11]. The main aim of this paper is to investigate and discuss the influence of freeze-thaw cycles on the performance of ISS treatment of expansive soil. It is anticipated that this work will help provide a theoretical basis for rational use of ISS in expansive soils in Northern China. The TG series of ISS is adopted for soil treatment in this paper, which is a new kind of soil stabilizer agent in China with many good characteristics (e.g., environmental friendly, good permeability, low cost and less dosage, etc.) [12, 13].

Soil Sample and Testing Method

An ISS solution with a dilution ratio to water of 1:200 was mixed with expansive soil in proportions of 16%, 22%, and 28%. These mixtures were then stored in a closed container for one week to ensure homogeneous mixing of the curing agent solution.

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TABLE 1

Sample	Natural water content (%)	Natural density (g/cm^3)	Proportion Δs	Liquid limit W_L (%)	Plastic limit W_p (%)	Plasticity index I_p	Free swelling ratio (%)	Maximum dry density (g/cm^3)	Optimum water content (%)
Expansive soil	22.4	2.18	2.74	61.6	19.9	41.7	78	1.77	18.9
ISS reinforced	–	–	–	53.5	23.6	29.9	42	1.81	14.9

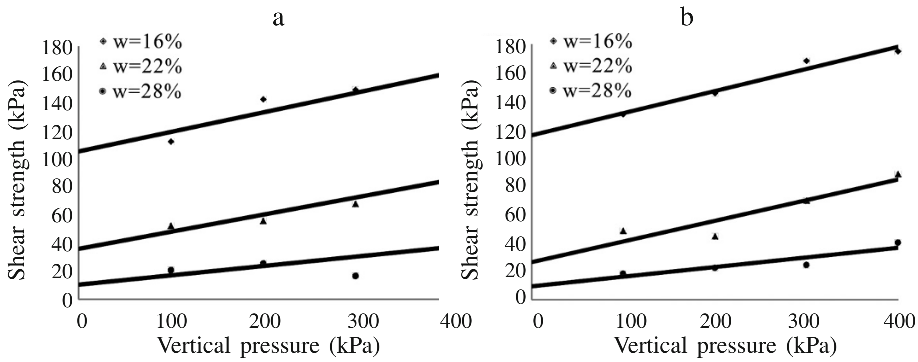

Fig. 1. Graphical illustration of the influence of moisture content on the shear strength of: a) raw expansive soil and b) ISS expansive soil.

As controls, samples were also mixed with water in the same proportions (16%, 22%, and 28%). The error in proportions was ±2%. The physical and mechanical properties of a sample, before and after treatment with ISS, are shown in Table 1 [10].

The sample shown in Table 1 has a free swelling ratio of 78% and is classified as a normal expansive soil [11] as it is in the 65-90% free swelling range. Furthermore, the sample has a liquid limit of 61.6% (>50%), and the particle size content <0.075 mm is greater than 50%, resulting in its classification as a high liquid limit clay soil [10].

The expansive soil samples were divided into two groups: pure expansive soil and those treated with ISS. Each group consisted of samples with different moisture contents (16%, 22%, and 28%). Each sample was made into a cylinder 20 mm in height, with a diameter of 30.9 mm and initial dry density of 1.65g/cm^3. Drained shear tests were conducted on these samples at room temperature at a shear rate of 0.02 mm/min (Specification of Soil Test in China [14-15]).

Freeze-thaw cycle tests were conducted in a closed test box without external water supply. The freezing and thawing temperatures were −15°C and 20°C (room temperature), respectively. The duration of freezing was set to ten days, and the duration of thawing to five days. Shear tests were also conducted on samples after one, three, five, and seven freeze-thaw cycles. Samples were then imaged after freeze-drying using scanning electron microscopy (SEM), followed by calculation of soil porosity.

Results and Analysis

The tests show that the moisture content influences the strength of expansive soil both before and after treatment with ISS. Increasing moisture content reduces the strength of expansive soil, especially in the reinforced sample. Conversely, the cohesive strength of the treated sample is also greatly reduced, although the friction angle changes very little regardless of whether the sample is treated or not.

The influence of moisture content on shear strength

Figure 1 shows the relationship between vertical pressure and shear strength in expansive soil with different moisture contents at room temperature and for samples treated with ISS. It is evident that the shear strength of the expansive soil decreases greatly with increasing moisture content. However, the

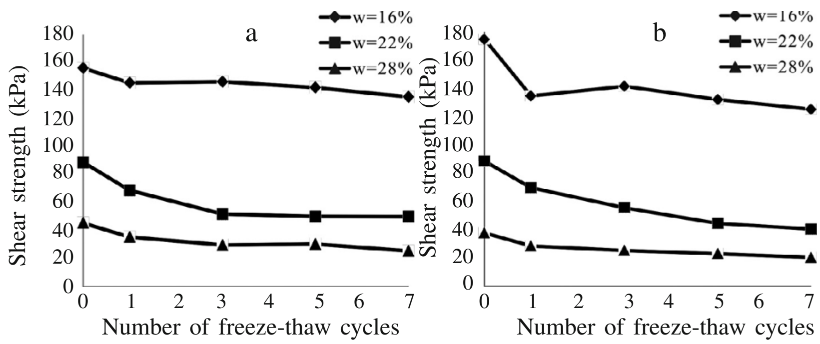

Fig. 2. Graphical illustration of the changes of: a) shear strength of raw expansive soils and b) ISS expansive soil subjected to freeze-thaw cycles at a vertical pressure of 400 kPa.

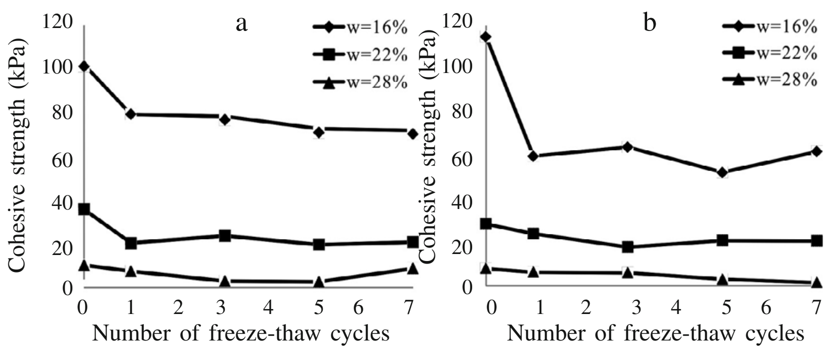

Fig. 3. Graphical illustration of the changes of cohesion strength of: a) untreated expansive soil and b) ISS-treated expansive soil subjected to freeze-thaw cycles.

strength of treated samples is higher than that of the pure expansive soil when the moisture content is close to the plastic limit. When the moisture content increases, the effect of ISS on soil strength becomes less obvious.

The influence of freeze-thaw cycles on shear strength

Figure 2(a) shows the relationship between shear strength and freeze-thaw cycles for untreated samples of different moisture contents (16%, 22%, and 28%) subjected to a vertical pressure of 400 kPa. Figure 2(b) shows the same relationship, but for ISS-treated expansive soil. It is evident that the shear strengths for both samples decrease with increasing freeze-thaw cycles. The greatest change occurs after one cycle, and the minimum value of shear strength is reached after about seven cycles.

Importantly, Fig. 2(a) shows that moisture content has the greatest influence on soil strength: shear strength is highest (~160 kPa) at a moisture content of 16% (close to plastic limit) but is significantly reduced (~40 kPa) at a moisture content of 28% (close to liquid limit).

The shear strength of expansive soil treated with ISS starts at 180 kPa, while it only starts at 160 kPa for untreated samples. After one freeze-thaw cycle, the strength of expansive soil is lower than that of the untreated samples, inferring that expansiveness is temperature sensitive. However, the strength of both samples decreases with increasing freeze-thaw cycles, whether treated with ISS or not, and both samples reach minimum values after seven cycles. These results suggest that moisture content plays a leading role in soil strength.

The influence of freeze-thaw cycles on soil cohesion

The cohesive strengths of expansive soils and samples treated with ISS with different moisture contents are shown in Fig. 3 as a function of freeze-thaw cycles. Regardless of treatment, both types of

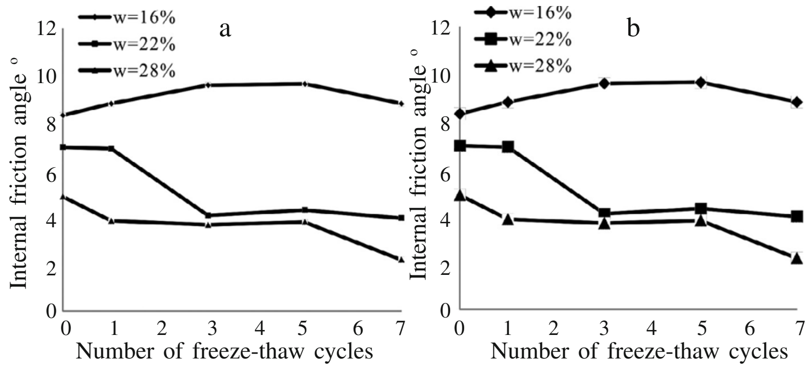

Fig. 4. Graphical illustration of the changes of internal friction angle in: a) raw expansive soil and b) ISS-treated expansive soil subjected to freeze-thaw cycles.

expansive soil show a decrease in cohesive strength with increasing freeze-thaw cycles, although stabilization occurs after seven cycles. Cohesive strength is highest when the moisture content reaches 16%. At this point, cohesive strength of the ISS-treated sample is 115 kPa, but only 100 kPa for the untreated sample. With increasing moisture content, the strength of both samples decreases, reaching a minimum value of 10 kPa at a moisture content of 28%.

When the moisture content reaches 16%, the thickness of the particle-bound moisture film is modified by ISS and decreases, thus reducing the distance between particles. With the increase in grain contacts and attraction of soil particles, the cohesive strength of the modified soil increases more so than in the untreated soil. After a freeze-thaw cycle, the expansion and contraction of bound-water and free water in the soil results in soil particle detachment. Untreated samples have a higher clay content, resulting in soil particles becoming coherent again as temperatures rise and ice melts. At the same time, the films of bound-water become thin around the expansive soil particles modified by ISS and moisture occurs mostly as free water. Thus, the soil treated with ISS suffers a larger strength reduction than the untreated samples after a freeze-thaw cycle. During further freeze-thaw cycles, the strength of both treated and untreated samples is reduced, but only marginally. The strength reduction is related to increasing moisture content, suggesting that this is a major factor in soil strength.

The effect of freeze-thaw cycles on friction angle of soil

Changes in the internal friction angle of untreated expansive soil as a function of freeze-thaw cycles are shown in Fig. 4(a). The same is shown for expansive soil treated with ISS in Fig. 4(b). Both treated and untreated soils show minor changes in internal friction angle within the 2-12° range as a result of freeze-thaw cycles. However, the internal friction angle does show a marked decrease with increasing water content. According to Fig. 4, the internal friction angle changes most significantly with freeze-thaw cycles when the moisture content is >16% and <28%. The internal friction angle reaches a minimum after three to five freeze-thaw cycles.

The internal friction angles are not large and when the moisture content is 28% (close to the liquid limit), the pore water pressure and shear strength are low, resulting in a decrease in frictional force, and so the internal friction angle tends towards zero.

The influence of freeze-thaw cycles on porosity

To investigate changes in porosity with freeze-thaw cycles, both the ISS-treated soils and untreated soils are subjected to the following: one group of sample is not subjected to freeze-thaw cycles (Fig. 5 (a) and (d)), one is subjected to a single freeze-thaw cycle (Fig. 5 (b) and (e)) and another to five freeze-thaw cycles (Fig. 5 (c) and (f)). The samples are then freeze dried and imaged using SEM. The porosity is then calculated from binary SEM images.

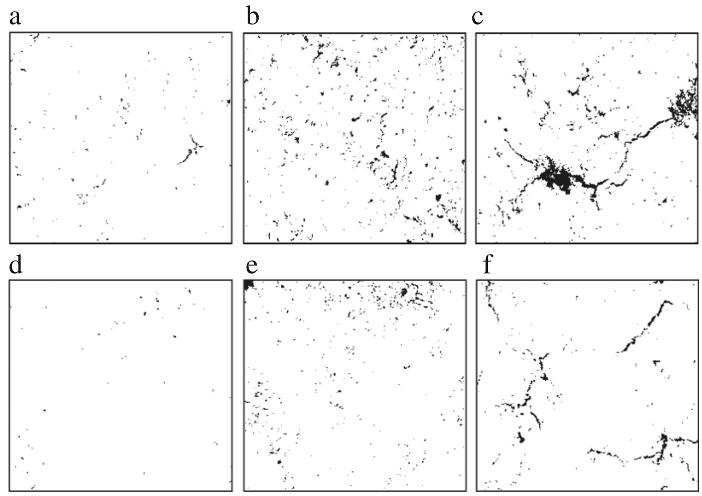

Fig. 5. Binary SEM images obtained after different cycles of freeze-thaw. The porosity of: a) unfrozen expansive soil, b) soil after one freeze-thaw cycle, and c) soil after five freeze-thaw cycles; d) treated with ISS unfrozen expansive soil, e) treated with ISS soil after one freeze-thaw cycle, and f) treated with ISS soil after five cycles of freeze-thaw.

The image analysis reveals that the porosity of expansive soil increases with the number of freeze-thaw cycles. The porosity of soil treated with ISS is lower and changes to a lesser degree during freeze-thaw cycles than for untreated expansive soil. This indicates that ISS has a significant effect on treating expansive soils by reducing porosity and increasing density compared with untreated soil at the same level of compaction.

Conclusions

1. ISS can effectively improve the strength of expansive soil when its moisture content is close to the plastic limit. However, strength decreases with increasing moisture content, as evidenced by the shear strength being reduced to ~30 kPa at a moisture content of 28%.

2. The strength of samples is reduced with increasing numbers of freeze-thaw cycles, reaching the lowest values after seven cycles. Compared with untreated expansive soil, the strength of soil treated with ISS is lower and changes more significantly.

3. The cohesive strength of expansive soil decreases with increase in the number of freeze-thaw cycles, regardless of whether the soil is treated with ISS or not. Cohesive strength reaches its lowest value when it stabilizes, but is highest when the moisture content of soil is close to the plastic limit. With increasing moisture content, the cohesive strengths of these two kinds of soil both decrease, and they decrease to a minimum after seven freeze-thaw cycles.

4. The internal friction angle is small, regardless of whether the expansive soil is treated or not, and it changes little with increasing numbers of freeze-thaw cycles.

5. The porosity of expansive soil increases with freeze-thaw cycles for treated and untreated samples, and the change in porosity is largest after the first freeze-thaw cycle. The porosity of ISS-treated samples is low and changes little with increasing freeze-thaw cycles, but untreated expansive soils have a comparatively larger porosity that undergoes more significant changes during freeze-thaw cycles than the treated samples.

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