

Article

Experimental Study on Engineering Characteristics of High-Speed Railway Subgrade Filler in Island Permafrost Regions

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Abstract: The high-speed railway (HSR) subgrade has a strict settlement-control standard at the mm level, but its deformation stability is significantly threatened on permafrost with poor thermal stability and in susceptible-to-thawing settlements. Therefore, the filler suitable for permafrost regions needs to be explored and determined. In this study, the frost heaves, permeabilities and static strength characteristics of three coarse fillers were experimentally investigated, and the optimal subgrade filler was determined for the certain HSR, the first HSR in permafrost regions around the world. The test fillers include pure fillers, 5% cement improved fillers and 5% cement + 3% modifier improved fillers, and the effects of curing time, modifier content and freeze–thaw cycles were analyzed. The test results show that: (1) the frost heave rate and permeability coefficient decrease with the increase of curing time and modifier content, while increasing with the freeze–thaw cycles; (2) After six freeze–thaw cycles, the cement + modifier improved filler’s frost heave rate and permeability coefficient are 0.51 and 0.00331 cm/s, a larger decrease in the frost heave rate (more than 50%) and the permeability coefficient (about one order of magnitude) than that of pure filler; (3) The cement + modifier improved filler shares the highest compressive strength under different curing times and freeze–thaw cycles. In summary, the modifier has a more significant influence on the engineering characteristics than the curing time or freeze–thaw cycles, and the cement + modifier improved filler has the best comprehensive performance. This study will provide a technical reference for the foundation-treatment and disease-prevention of HSRs in island permafrost regions.

Keywords: island permafrost; high-speed railway; improved subgrade filler; permeability characteristics; frost heave rate



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1. Introduction

The certain high-speed railway (HSR) is planned to be built in the high-latitude island permafrost regions in cold regions of China. It is the first high-speed railway to cross the permafrost regions in the world. Usually, island permafrost is discontinuous, with a small thickness and shallow burial. Most of them are high-temperature ($0\text{ }^{\circ}\text{C} > T > -0.5\text{ }^{\circ}\text{C}$) and extremely unstable, which easily suffers large uneven settlements and endangers railway stability [1–5]. During the construction of road engineering in island permafrost regions, shallow-island permafrost with a high ice content needs to be excavated and replaced with improved soil. The use of improved soils with good physical and mechanical properties will effectively improve the quality of road construction. Fentaw et al. found that the expansive soil strength of subgrade soil was increased by using waste marble dust, rice husk ash and cement by mixing in an appropriate proportion [6]; 5% fly ash and 3% cement have been used to improve the strength of fresh cohesive soil, which satisfied the subgrade requirement [7]; Zhu et al. studied the mechanical properties of lime soil modified by high-content soda residue and explored the material strength-enhancement

mechanism to provide a reference for the large-scale utilization of solid-waste soda residue in road engineering [8]. Yin et al. found that stabilized black cotton soil with 3% lime +20% volcanic ash met the minimum swell, plasticity and strength requirements, and thus can be used as an alternative to cutting and filling in pavement subgrade construction [9]. Ma et al. analyzed the properties of the modified red mud using a modifier and evaluated road performance of the modified Bayer red mud as subgrade filler by a real highway project [10].

Coarse-grained soil is generally used as filler for HSR subgrade in cold regions of China. Luo et al. conducted a series of 1D freezing tests on coarse-grained soil based on orthogonal array to study the frost heave characteristics under the combined actions of moisture content, fine particle content, dry density and cooling temperature [11]. The average frost heave rate was used as the index to evaluate the frost heave sensitivity. She et al. believed that a higher fines content would lead to the continuous frost heave of coarse-grained soil by testing the frost heave rate of coarse-grained soil samples with different fine contents in the fully saturated state [12]. Wang et al. studied the frost heave characteristics of coarse-grained soil samples with different fine-grained contents, dry densities, overburden pressures and water supplies through a frost heave test and compaction test, analyzed the influence of overburden pressure on cumulative frost heave, and obtained the best fine-grained content of coarse-grained soil with a good compaction effect and frost heave resistance [13]. The influence of fine particle content and gradation on the frost heave characteristics of coarse filler has also been studied [14–17], but the detailed frost heave mechanism of coarse-grained soil was neglected [18–20]. By analyzing the influence of cement content and filler particle-size grade on the compaction effect, frost heave performance and freeze-thaw durability of gravel subgrade, Long et al. proposed different cement contents and fine particle contents according to different permeability requirements of their projects [21–28]. Zhao et al. studied the influence of different cement contents on the mechanical properties, dry shrinkage characteristics and frost heave sensitivities of the graded crushed stone layer of the HSR subgrade, and obtained the best cement content and water–cement ratio through comprehensive analysis [29]. Through a comparative analysis based on a series of unidirectional frost heave tests on well-graded gravel soil, it was concluded that the water content has the greatest impact on the final frost heave, followed by porosity and fine particle content [30,31]. However, previous studies mainly focused on the coarse–fine mixed filler in seasonal frozen regions, and were generally limited to the single-performance test of cement improved filler. Therefore, research is still rare on the appropriate improvement schemes for pure coarse-grained filler in permafrost regions. Moreover, the comprehensive understanding of engineering performance of modified fillers considering permeability, frost heave and strength are limited.

In this study, the frost heaves, permeabilities and compressive strengths of three fillers were experimentally investigated under the different curing times, modifier contents and freeze-thaw cycles. The test fillers included pure fillers, 5% cement improved fillers and 5% cement +3% modifier improved fillers. The performances of the three fillers under different influence conditions are revealed, and the optimal improvement scheme is given based on the test results. This research can provide a reference for the foundation treatment of the certain HSR subgrade and future permafrost regions' HSRs.

2. Test Materials and Methods

2.1. Test Materials

The test materials were taken from the filling site of the newly built the certain HSR, and the maximum dry density of the filler was 2.09 g/cm^3 . The subgrade replacement filler retrieved from the site was screened by the water-washing method. The washed soil samples of each particle group were put into the drying box and dried at 60°C for 24 h. The excavated samples were weighed, respectively, to obtain the original grading curve of the filler, as shown in Figure 1. Due to the size limitation of the laboratory equipment, the maximum particle size allowed in the test was 20 mm, and the filler particles larger than

20 mm were equivalently replaced according to “Code for Soil Test of Railway Engineering” (TB 10102-2010). The formula for calculating the content of each group of equivalent replacement is shown in Equation (1):

$$P_i = \frac{P_5}{P_5 - P_{d,max}} P_{0i} \quad (1)$$

where P_i is the content of a particle group of the soil sample after replacement (%); P_5 is the content of particle group with an original grade greater than 5 mm (%); $P_{d,max}$ is the content of oversized particles (%); and P_{0i} is the content of a grain group in the original soil sample (%).

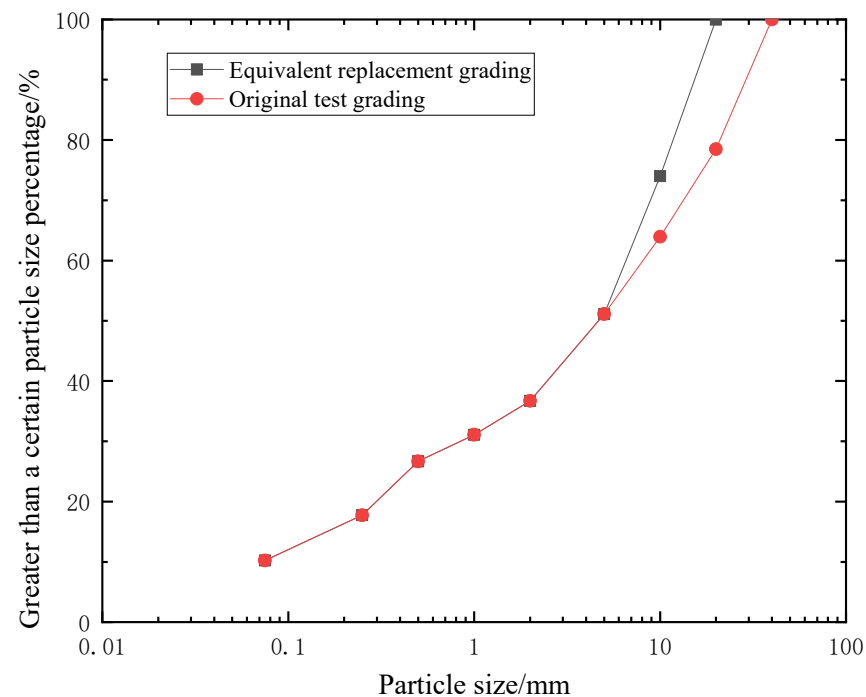


Figure 1. Comparison between original grading and equivalent replacement grading.

In this study, ordinary Portland cement (P.O 42.5) and high-performance frost heave modifier were applied to improve the filler; the main components of ordinary Portland cement are shown in Table 1. The frost heave modifier was a non-toxic, environmentally friendly, harmless gray powder inorganic compound, made of mineral materials in a particular proportion, e.g., NaNO_3 , Na_2CO_3 , Na_2SO_4 , CaCl_2 , CaCO_3 , CaO , etc., after high-temperature activation and ultra-fine grinding. After being evenly mixed with cement, the modifier had an electrochemical reaction with cement when it met water, enhancing the soil's compactness strength and improving its impermeability, frost resistance, durability and stability. As the modifier is being applied for intellectual property protection, detailed information cannot be provided yet. The frost heave resistance, permeability and compressive strength of the pure, cement improved and cement + modifier improved fillers were studied.

Table 1. Main components of ordinary Portland cement (P.O 42.5).

Main Components	$3\text{CaO} \cdot \text{SiO}_2$	$2\text{CaO} \cdot \text{SiO}_2$	$3\text{CaO} \cdot \text{Al}_2\text{O}_3$	$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	CaSO_4
Content/%	36~60	15~37	7~15	10~18	3~5

2.2. Test Equipment

The tests carried out in this study mainly included the freeze–thaw test, permeability test and strength test. The test equipment is shown in Figure 2; all test processes referred to the “Code for Soil Test of Railway Engineering” (TB 10102-2010).

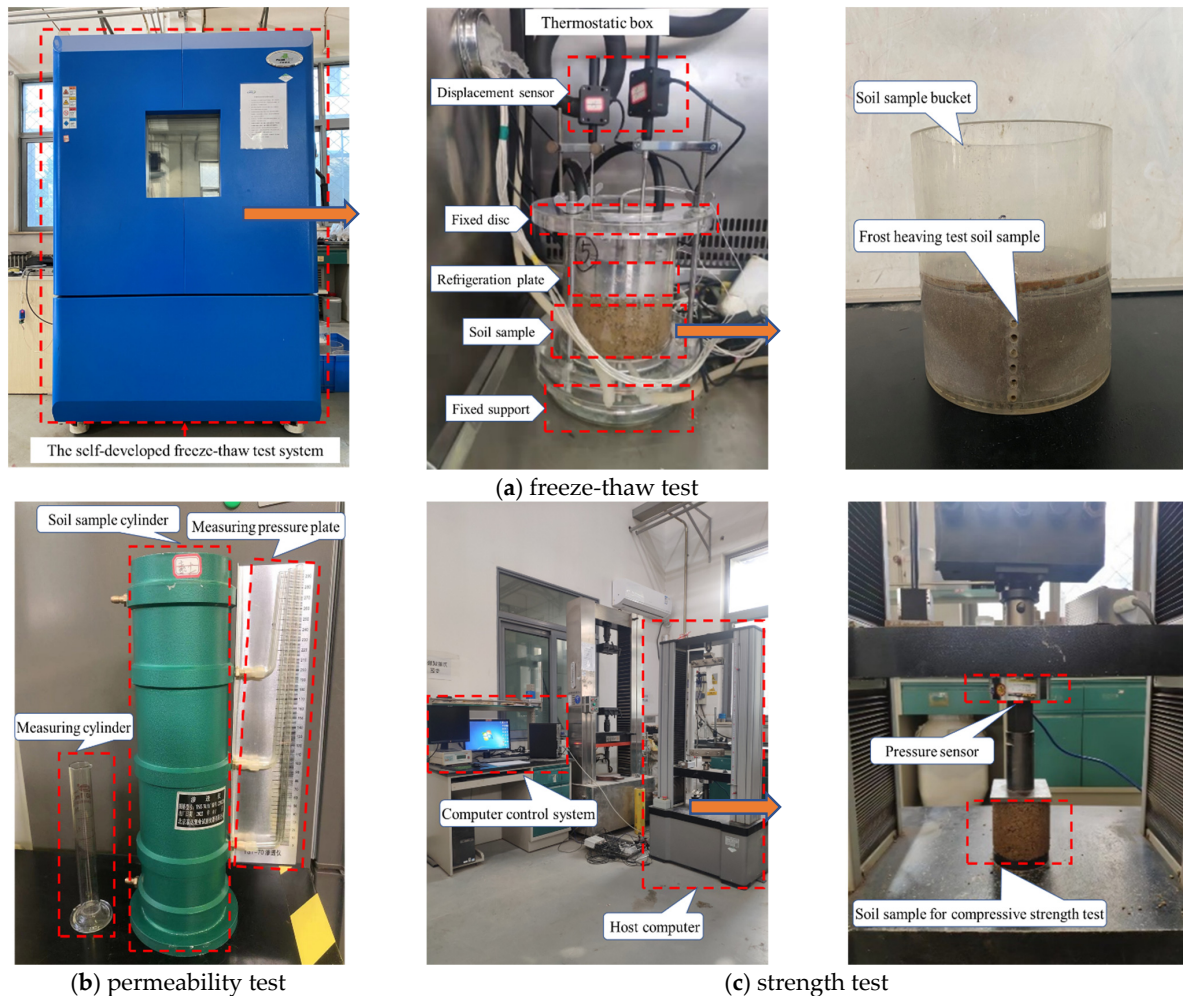


Figure 2. Test equipment.

(1) Frost heave test

The frost heave rate test adopted the self-developed freeze–thaw test system, as shown in Figure 2a. It mainly included a temperature-control system with a range of $-20\sim 50\text{ }^{\circ}\text{C}$, a displacement monitoring system, a thermostatic box, a cold bath system, etc. Figure 2a shows the installed frost heaving sample. The bottom and top of the sample were fixed to a support and refrigeration plate, respectively. The temperatures of the top and bottom plates were adjusted through the cold bath, which could simulate the unidirectional freezing of the soil samples. Two displacement sensors were arranged on the top of the refrigeration plate (the range was $-30\sim +30\text{ mm}$ and the accuracy was 0.1 mm), which could monitor the displacements and deformations of the soil samples in real time. The height of the soil sample was 8 cm , and the diameter of the sample was 15 cm .

After the sample was installed, the thermostatic box and the cold plates were set to $1\text{ }^{\circ}\text{C}$ and kept for 6 h . The test started after the initial temperature of the sample reached $1\text{ }^{\circ}\text{C}$ and remained stable. First, the temperature of the top plate was set to $-15\text{ }^{\circ}\text{C}$ for half an hour to allow the top surface of the sample to freeze quickly. After that, the top plate’s temperature was adjusted to $-2\text{ }^{\circ}\text{C}$ and maintained a cooling rate of $0.3\text{ }^{\circ}\text{C/h}$ for cooling. The cooling process lasted for 72 h . During the test, the temperature of the thermostatic box

and the test bottom plate was always maintained at 1 °C. After the test, the frost heave rate could be calculated according to the deformation-monitoring data. Then, the sample was put into the curing box for 24 h and continued to test the frost heave rate until reaching the planned freeze–thaw cycles.

(2) Permeability test

The constant-head permeability test was applied to the permeability test. During the test, the head height and seepage flow were measured at different device points so as to calculate the seepage velocity and hydraulic gradient. The calculation formula of the permeability coefficient is shown in Equation (2) [32]:

$$v = ki \quad (2)$$

where v is the seepage velocity of the soil sample (cm/s); k is the permeability coefficient of the soil sample (cm/s); and i is the hydraulic gradient.

The instrument used in the test was a tst-70 constant-head permeameter (Hebei Zhongke Beigong Test Instrument Co., Ltd, Cangzhou, China), as shown in Figure 2b, including a sample cylinder, measuring pressure plate, water supply bottle and measuring cylinder.

(3) Strength test

A WDW-50 universal testing machine (Jinan Hengsi Shengda Instrument Co., Ltd, Jinan, China) was used for the unconfined compressive strength test, as shown in Figure 2c. The testing machine was mainly composed of a host computer, computer control system and accessories. The maximum test force is 50 kN, the accuracy of the test force was $\pm 0.5\%$, and the loading speed was 0.01–500 mm/min. The sample size in the compressive strength test was 10×10 cm cylinder.

2.3. Test Plan

The test item included the frost heave test, the permeability test and the static-strength test, and the filler included the pure filler, the 5% cement improved filler and the 5% cement +3% modifier (proportion in cement quality) improved filler. The test scheme is shown in Table 2. The test process referred to the “Code for Soil Test of Railway Engineering” (TB 10102-2010). Three tests were conducted for each test item under the same test conditions, the average value of the three tests was taken as the final test results and the standard deviation of the results was obtained. Based on the test analysis results, the engineering characteristics of the different fillers were clarified, and the optimal improvement method was obtained.

Table 2. Test plan.

Test Items	Modifier Dosage	Curing Time/d	Freeze–Thaw Cycles
Frost heave test	0%	3/7/15/21/28	1/2/3/4/5/6
	5% cement		
	5% cement + 3% modifier		
Penetration test	0%	3/7/15/21/28	0/2/4/6/8
	5% cement		
	5% cement + 3% modifier		
Strength test	5% cement	3/7/15/21/28	0/2/4/6/8
	5% cement + 3% modifier		

Note: a freeze–thaw cycle is defined as the samples are kept for 24h at -20 °C and 20 °C, respectively.

As according to the “Code for Design of Railway Earth Structure” (TB10001-2016), the compaction degrees of test samples were controlled to 0.95.

3. Results and Analysis

3.1. Frost Heave Rate

3.1.1. Influence of Curing Time

Figure 3 shows the influence of curing time on the frost heave rates of the fillers. It can be seen that the frost heave rate from high to low is pure filler, cement improved filler and cement + modifier improved filler. The frost heave rate of the three fillers decreases with the increasing curing time, but the reduction process is quite different. Specifically, the frost heave rates of the pure and cement + modifier improved fillers tend to be stable after 15 days of curing, while the frost heave rate of cement improved filler continues to decrease. After 28 days of curing, the frost heave rate of cement + modifier improved filler is the lowest, only about 1/4 of that of pure filler.

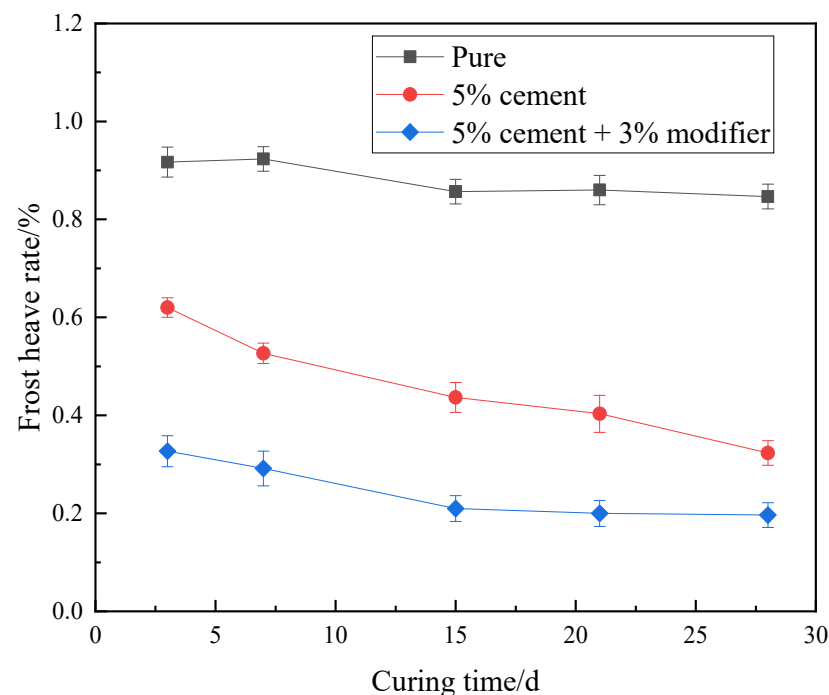


Figure 3. Influence curve of curing time on frost heave rate.

3.1.2. Influence of Freeze–Thaw Cycle

Figure 4 shows the influences of freeze–thaw cycles on the frost heave rates of each filler after curing for 7 days. According to the figure, the frost heave rates of the three fillers increase with the freeze–thaw cycles. Furthermore, there exists a stable freeze–thaw cycle, after which the frost heave ratio shows an insignificant increase. The stable freeze–haw cycles are five, four and three for pure filler, cement improved filler and cement + modifier improved filler, respectively. Among the three fillers, the frost heave rate of the cement + modifier improved filler is the lowest, which is about 58% lower than that of pure filler and about 40% lower than that of cement improved filler after six freeze–thaw cycles.

3.2. Permeability Coefficient

3.2.1. Influence of Curing Time

Figure 5 shows the influence curve of curing time on the permeability coefficient of filler. The permeability coefficients of the three fillers decrease with the increase in curing time, but show different characteristics. Among them, the permeability coefficient of pure filler continues to insignificantly decline with the curing time, the permeability coefficient of cement filler remains stable after 15 days, and the permeability coefficient of cement + modifier improved filler tends to stabilize after 7 days of curing. Overall, the

permeability coefficient from high to low is pure filler, cement improved filler and cement + modifier improved filler. After 28 days of curing, the permeability coefficient of the cement + modifier improved filler is the lowest, which is nearly two orders of magnitude lower than that of the pure filler.

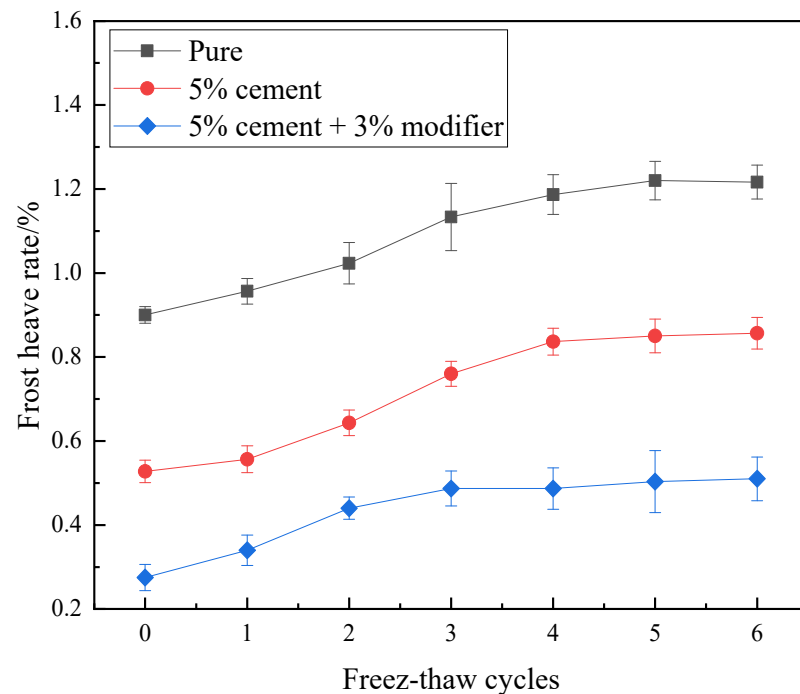


Figure 4. Influence curve of freeze-thaw cycles on frost heave rate.

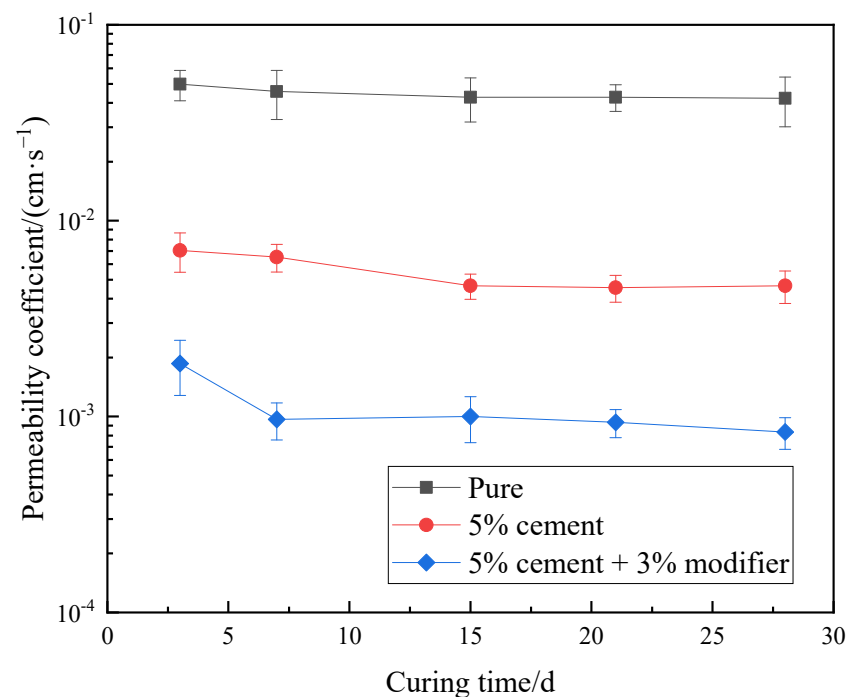


Figure 5. Influence curves of curing time on permeability coefficient.

3.2.2. Influence of Freeze–Thaw Cycle

Figure 6 shows the influence curve of freeze-thaw cycles on the permeability coefficient of each filler after curing for 7 days. It can be seen from the figure that under different freeze-thaw cycles, the permeability coefficient from high to low is pure filler, cement

improved filler and cement + modifier improved filler. The permeability coefficients of the three fillers increase with the increase of freeze–thaw cycles but show different characteristics. Among them, the permeability coefficient of pure filler tends to be stable after the sixth freeze–thaw cycle, while this critical cycle value is four and two for cement improved and cement + modifier improved filler, respectively. After eight freeze–thaw cycles, the permeability coefficient of cement + modifier improved filler is the lowest, which is about one order of magnitude lower than that of pure filler under the same conditions.

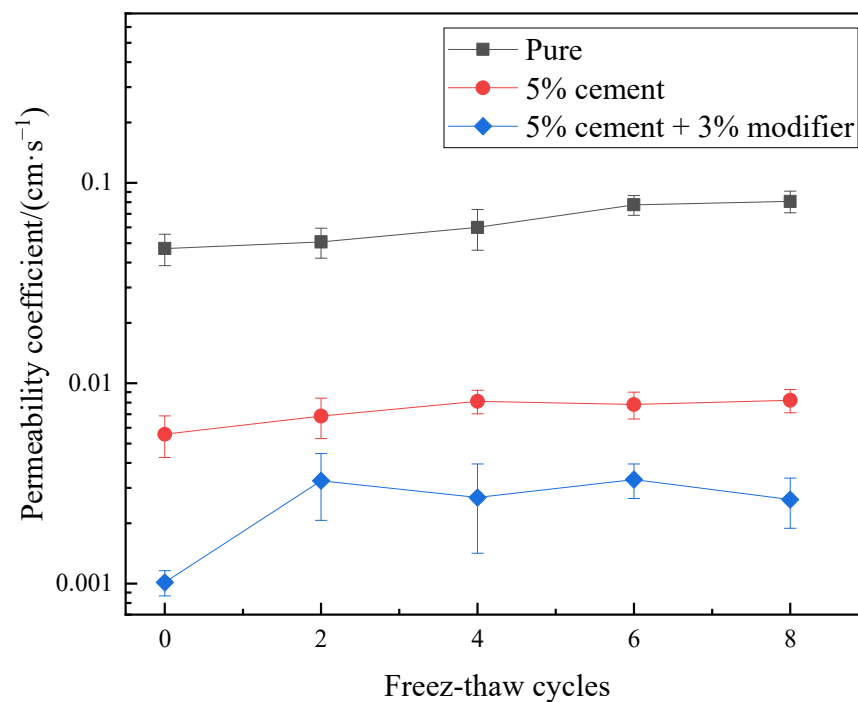


Figure 6. Influence curves of freeze–thaw cycles on permeability coefficient.

3.3. Compressive Strength

The coarse-grained soil shares a high coarse particle content and low cohesion (as can be seen in Figure 2). Therefore, the coarse-grained soil without cement is hard to use to form a stable soil sample [33]. Based on upper considerations, the influence of the curing time and freeze–thaw cycle on the compressive strength of the two improved fillers is analyzed.

3.3.1. Influence of Curing Time

Figure 7 shows the influence curves of curing time on the compressive strengths of the improved fillers. It can be seen from the figure that under each curing time, the compressive strength from high to low is cement + modifier improved filler and cement improved filler. With the increase in curing time, the compressive strengths of the two kinds of improved fillers show an increasing trend, but this increasing trend is more significant for the cement + modifier improved filler. After curing for 7 days, the compressive strengths of both fillers increased significantly, and the compressive strength of the cement + modifier improved filler increased at a rate of approximately 0.06 MPa/d, about twice that of the cement improved filler. When cured for 28 days, the compressive strength of the cement + modifier improved filler is the highest, about 1.3 times that of the cement improved filler.

3.3.2. Influence of Freeze–Thaw Cycle

Figure 8 shows the influence curve of freeze–thaw cycles on the compressive strengths of the fillers after curing for 7 days. It can be seen from the figure that under different freeze–thaw cycles, the compressive strength of the cement + modifier improved filler is greater than that of the cement improved filler. After the second freeze–thaw cycle, the

compressive strength of the cement + modifier improved filler tends to be stable, while the compressive strength of the cement improved filler continues to decline. After the eighth freeze–thaw cycle, the compressive strength of the cement + modifier improved filler is the highest, which is about 1.6 times higher than that of the cement improved filler.

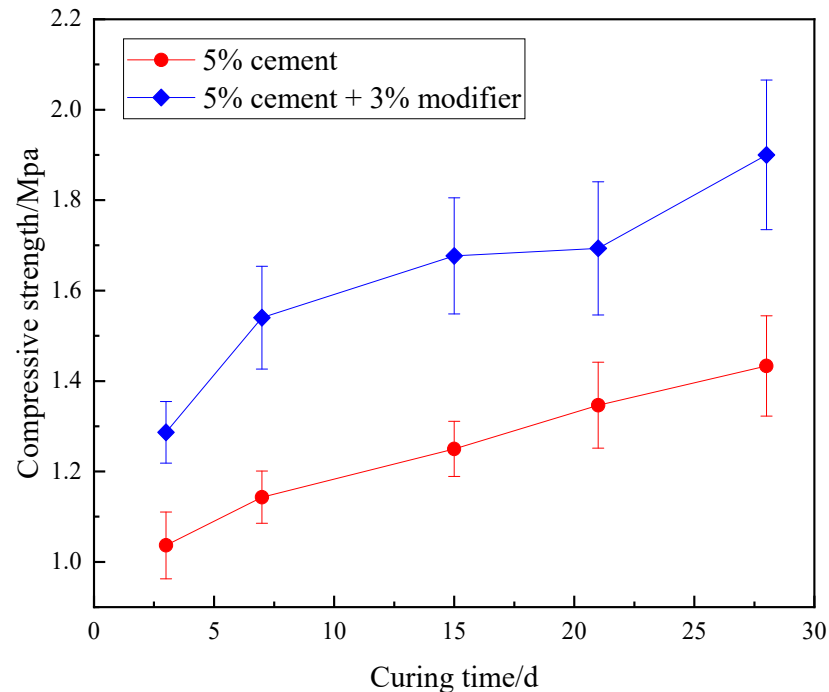


Figure 7. Influence curves of curing time on compressive strength.

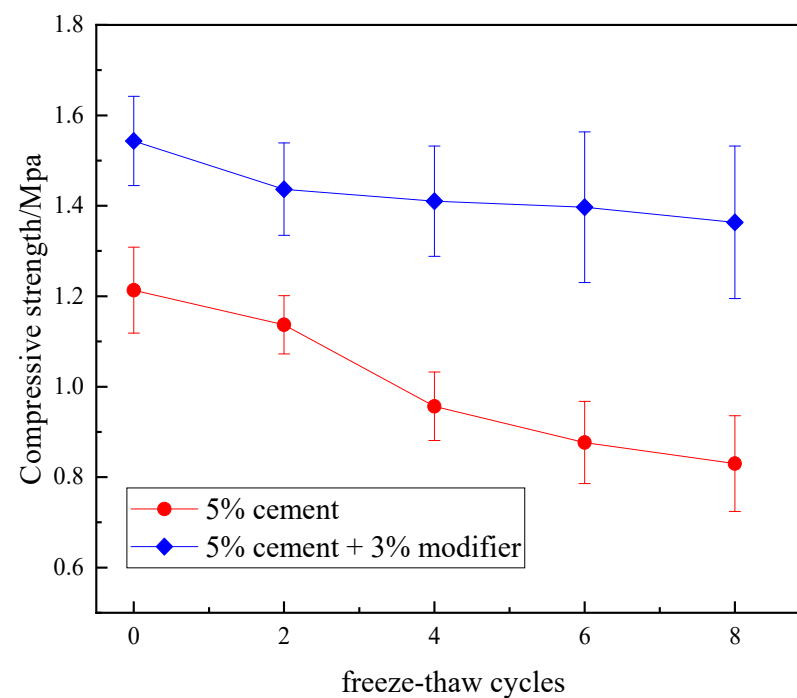


Figure 8. Influence curves of freeze–thaw cycles on compressive strength.

4. Discussion

The following section combines this study's field test with previous research findings to summarize and discusses the characteristics and mechanism of the improved filler in island permafrost regions.

4.1. Field Test

After the shallow permafrost of the foundation was excavated, the improved filler was backfilled in three layers. After that, the dynamic deformation modulus test (Evd) and plate load test (K30) were, respectively, conducted for the cement improved filler and the cement + modifier improved filler (Figure 9). The test results of the two kinds of improved filler met the requirements of the “Standard for Acceptance of Earthworks in High-speed Railway” (TB10751-2018). Overall, the test results of the same filler in different layers are similar. Specifically, for the 5% cement improved filler, the Evd is about 80.5~82.5 MPa and the K30 is about 179.5~182.5 MPa/m. For the 5% cement + 3% modifier modified filler, the Evd is about 89.8~93.3 MPa and the K30 is about 191~193.5 MPa/m. The field test results reveal that the field performance of the cement + modifier modified filler is obviously better than that of the cement modified filler.

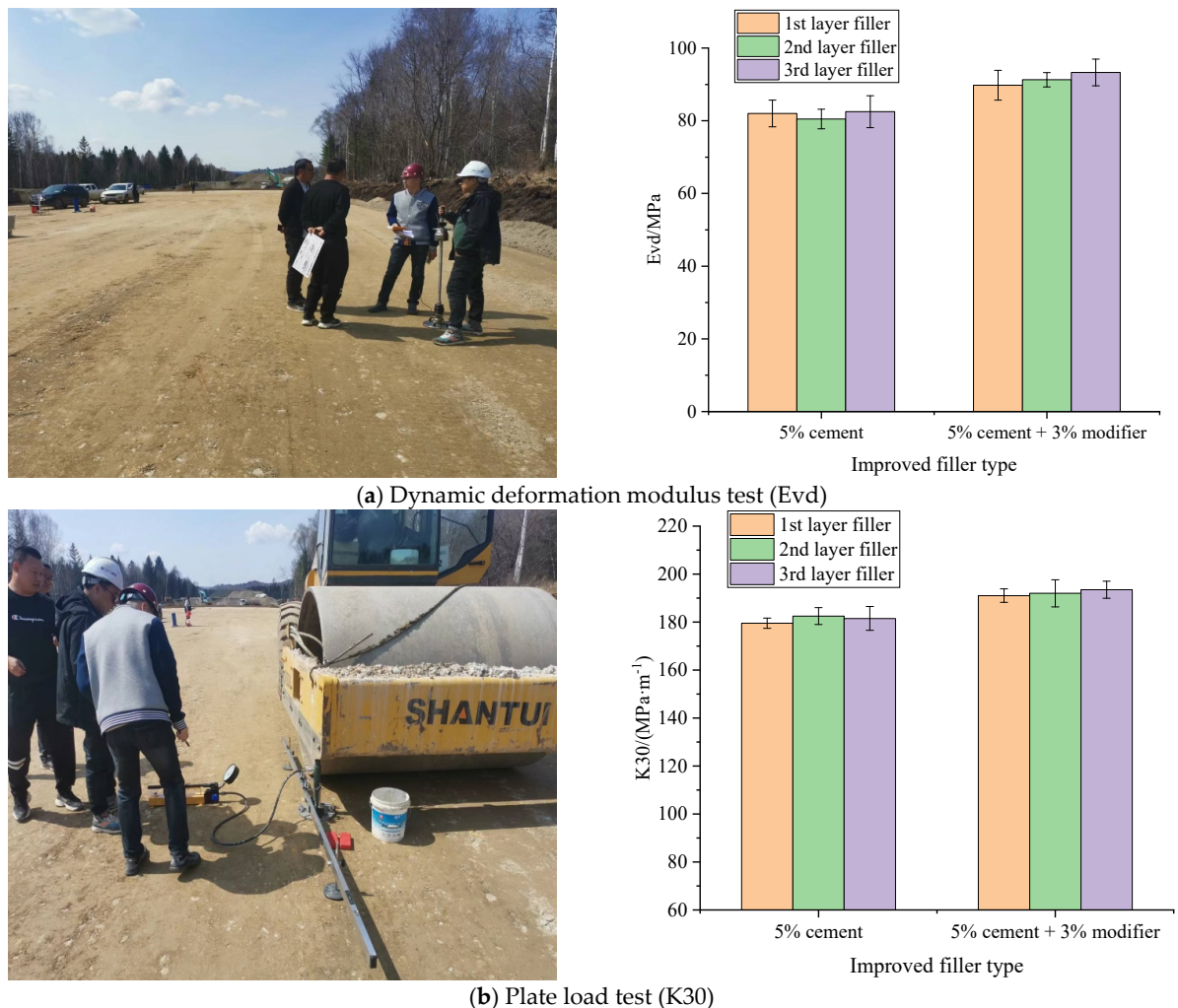


Figure 9. Improved filler dynamic deformation modulus test and plate load test.

4.2. Improving Mechanism

By analyzing the effects of different curing times, modifier contents and freeze–thaw cycles, it can be demonstrated that the modifier content has the most significant impact on the engineering characteristics of the improved filler, especially in terms of permeability coefficient. Specifically, the permeability coefficient of the cement + modifier improved filler is about two orders of magnitude lower than that of pure filler. The main reason is that the cement and coarse grained soil react as follows:

(1) Ion exchange and adsorption

Among the colloids formed by cement hydration and soil particles, Ca^{2+} , OH^- and $\text{Ca}(\text{OH})_2$ coexist, while soil particles show colloidal characteristics when combined with water, usually with K^+ , Na^+ and other ions on their surfaces. The Ca^{2+} released from cement hydration will exchange with the K^+ and Na^+ carried by soil particles in equal amounts. $\text{Ca}(\text{OH})_2$ in the colloid has a strong adsorption activity, which further binds the soil particles to form a stable cement soil chain-link structure, and has the function of sealing the pores between soil groups, which reduces the permeability coefficient of the improved filler, thereby reducing the frost heave rate.

(2) Hardening condensation reaction

As more and more Ca^{2+} is produced in the cement-hydration reaction, when the amount of Ca^{2+} exceeds the demand for ion exchange in (1), the excess Ca^{2+} will react with the SiO_2 and Al_2O_3 in clay minerals in an alkaline environment, which generates the stable crystalline minerals $\text{CaO} \cdot \text{SiO}_2 \cdot (n+1)\text{H}_2\text{O}$ and $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot (n+1)\text{H}_2\text{O}$ that are insoluble in water. These hardening reactions produce a strong chemical bond network crystal structure, which improves the strength and stability of filler.

On this basis, the high-performance modifier can accelerate the disintegration of cement particles, increase the specific surface area of cement so as to speed up the hydration of cement and finally make the cement completely hydrated, giving full play to the cementation of cement; the modifier can react with cement and metal elements contained in the soil to produce an electrolyte solution, and its concentration increases with the progress of oxidation reaction. The higher the concentration of the electrolyte solution, the faster the oxidation rate of metal elements in the soil, and the better the solidification effect of the soil. Therefore, the improver will significantly improve the process and efficiency of cement-improved coarse-grained soil “Ion exchange and adsorption” and “Hardening condensation reaction”, further increasing the compressive strength of the improved filler and reducing the permeability coefficient and frost heave rate.

In addition, the curing time and freeze–thaw cycles also impact the filler’s frost heave rate and compressive strength, indicating that the influence of these two factors should also be considered. However, the freeze–thaw induced by climate change cannot be avoided in engineering practice. Therefore, attention should be paid to the curing time; that is, the curing time of the improved filler should be guaranteed during the construction process.

4.3. Limitations of This Study

The influences of different cement contents (3% to 7%) on the engineering properties of coarse-grained soil fillers has been sufficiently studied [22,34–36]. Based on the previous comparative analysis, the anti freeze–thaw damage ability of the material was the best when the cement content increased from 3% to 5%. Therefore, 5% cement content was selected for this study. In terms of the modifier content, 3% modifier was preliminarily selected to investigate its improvement effect and control the engineering expense. Due to the requirements of the engineering schedule, the preliminary guidance of the improved filler for the construction is not reported yet. However, the optimal content and micro mechanism of the modifier are in continuous research.

In summary, with reference to the existing experimental research experience, 3% modifier was selected for the test. Later, the experimental research on the improved filler with different modifier contents will continue to be carried out in combination with the construction-application effect.

5. Conclusions

- (1) The double action of the modifier and cement effectively fills the pores between coarse grained soil, forming a strong soil-particle-bonding structure. The frost heave rate of the 5% cement + 3% modifier improved filler under the influence of various test factors is the smallest. After 28 days of curing, the frost heave rate (0.20) is about 1/4

- of that of pure filler. After six freeze–thaw cycles, the frost heave rate (0.51) is about 58% lower than that of pure filler, and the frost heave resistance effect is remarkable.
- (2) The modifier promotes the hydration reaction of cement and effectively seals the pores between coarse-grained soil. The permeability coefficient of the 5% cement + 3% modifier improved filler under the influence of various test factors is the lowest. After 28 days of curing, the permeability coefficient (0.0008 cm/s) is about two orders of magnitude lower than that of pure filler. After eight freeze–thaw cycles, its permeability coefficient (0.0026 cm/s) is one order of magnitude lower than that of pure filler, and its anti-permeability performance is the best.
 - (3) The hardening condensation reaction of the improved coarse-grained soil generates stable crystalline minerals and forms the strong chemical bond network crystal structure. The compressive strength of the 5% cement + 3% modifier improved filler under the influence of various test factors is the largest. After 28 days of curing, the compressive strength (1.9 MPa) is about 1.3 times higher than 5% cement improved filler. After eight freeze–thaw cycles, its compressive strength (1.36 MPa) is about 1.6 times higher than 5% cement improved filler, and the compressive strength is greatly improved.
 - (4) The modifier has a more significant influence on the engineering characteristics than the curing time and freeze–thaw cycles, and the engineering characteristics of the 5% cement + 3% modifier improved fillers are the best, which can provide technical reference for foundation treatment and engineering disease-prevention of HSR subgrade in island permafrost regions.

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