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Compressive and tensile properties of three fiber-lime-soils under freeze-thaw cycle

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Abstract: Generally, synthetic fiber, mineral fiber and plant fiber are added into soil to enhance the strength and deformation resistance of soil. The unconfined compressive test and splitting tensile test of three fiber-lime-soils under freeze-thaw cycle were carried out to study the variation of compressive and tensile properties of soil with freeze-thaw times. The test results showed that the optimum fiber rates of polypropylene fiber-lime-soil, basalt fiber-lime-soil and palm fiber-lime-soil were 0.2%, 0.2%, and 0.4% respectively, whether under freeze-thaw cycle or not. With the increase of freeze-thaw times, the compressive strength and tensile strength of the three fiber-lime-soils demonstrated phased downward trend, and the failure strains of fiber-lime-soil were greater than that of lime-soil. Under freeze-thaw cycle, the compressive strength, tensile strength, and deformation resistance of polypropylene fiber-lime-soil were better than those of basalt fiber-lime-soil and palm fiber-lime-soil. The interface force and the spatial constraint between fibers and soil particles enhanced the freeze-thaw durability of soil. By comparing and analyzing the test results of three types of fiber-lime-soil, it was found that the freeze-thaw resistance of polypropylene fiber-lime-soil was the optimum.

Keywords: fiber reinforced soil; fiber rate; freeze-thaw cycle; compressive strength; tensile strength

1 Introduction

A series of diseases, such as salt expansion, frost heave, thaw settlement, and hygroscopic softening, often occur in the saline soil of the coastal north China, which reduce the soil mechanical properties. In order to increase its strength, the saline soil is reinforced with fiber or solidified with cement and lime in engineering project[1]. The reinforcement materials can be divided into four categories, and the representative fibers[2−4] include: (1) synthetic fiber: polypropylene fiber, glass fiber, etc; (2) plant fiber: wheat straw, rice straw, coir, palm fiber, etc; (3) mineral fiber: basalt fiber, asbestos fiber, etc; (4) industrial wastes: tire strips, carpet threads, etc.

The fibers can enhance the mechanical properties of soil. Wei et al.[5] proved that wheat straw improved the compressive strength of soil, the soil deformation and the propagation of micro-cracks were restricted effectively. Chang et al.[6] added the curing agent and coir into the silty sand to improve its compressive strength. The coir hindered the propagation of micro-crack, and a certain toughness was produced in soil. Zhang et al.[7] reported that an appropriate ratio of palm fiber enhanced the compressive strength and shear strength of soil. The unconfined compressive strength test of polypropylene fiber-soil demonstrated that the compressive strength of soil increased with the increase of fiber ratio, while decreased as the fiber ratio exceeded the critical value. The optimum fiber content ranges from 0.2% to 0.5% of the dry soil mass[8]. The main function of fiber is to limit the development of micro-crack in soil, delay the soil failure, and improve the deformation resistance of soil[9]. Liu et al.[10] reported that adding 0.1% and 0.15% basalt fiber increased the compressive strength of nano SiO_2 concrete by 4.9% and 3.8%, respectively. Li et al.[11] found that the interface friction between tire strips and sand enhanced the tensile properties of soil by using waste tire strips as reinforcement materials.

The fiber-soil presents the phenomenon of “crack but not broken” in the tensile test. The fiber-soil enhances the plasticity of the soil, which can prevent the integral failure of the geotechnical building due to tensile cracking[12]. Zhang et al.[13] found that the tensile strength of gravelly clay increased with the increase of polypropylene fiber content. The tensile strength increased by 48.9% as the fiber content was 0.2%. Wang et al.[14] reported that the splitting tensile strength of reinforced loess first increased and then decreased with the increase of glass fiber content.

The destructive effect of soil subjected to freeze-thaw cycle is caused by the phase change and migration of water, the soil structure is destroyed under freeze-thaw cycle, and a large amount of micro-cracks are produced,

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which reduce the soil mechanical properties. Fiber restrains the relative sliding between soil particles, restricts the pore propagation and the soil deformation, thus improves the frost resistance of soil[15]. Si et al.[16] proved that the compressive strength of soil were enhanced by polypropylene fiber under freeze-thaw cycle. The compressive strength of fiber-soil first decreases rapidly, then decrease slowly, and finally tends to be stable with the increase of freeze-thaw times.

To date, few studies have focused on the mechanical properties of fiber reinforced soil subjected to freeze-thaw cycles and the mechanism of fiber to improve the soil freeze-thaw durability. Considering the large performance difference in various reinforcement materials, the unconfined compression test and splitting tensile test were carried out for comparative analysis of the compressive and tensile properties of lime stabilized soil (lime-soil for short), fiber and lime reinforced stabilized soil (fiber-lime-soil for short) under freeze-thaw cycles, Polypropylene fiber, basalt fiber and palm fiber were selected as reinforcement materials. And the freeze-thaw durability of fiber-lime-soil was evaluated.

2 Method

2.1 Materials

The soil, silty clay, was collected from Binhai New Area, Tianjin, China, its water content was 2.8% in air dried state. The maximum dry density and optimum water content of soil were obtained by modified compaction test. The physical property indices of soil are presented in Table 1.

Table 1 The physical properties indices of soil

Salt content /%	Plastic limit /%	Liquid limit /%	Plasticity index	Optimal water content /%	Maximum dry density /(g • cm^{-3})	Grain size distribution /%			
						>0.25 mm	0.25−0.075 mm	0.074−0.005 mm	<0.005 mm
2.93	17.6	29.7	12.1	16.8	1.71	1.68	6.85	76.25	15.22

The fiber reinforcement materials were polypropylene fiber, basalt fiber and palm fiber, and their physical and mechanical properties are shown in Table 2.

Table 2 The physical and mechanical properties of polypropylene fiber, basalt fiber and palm fiber[17−19]

Fiber type	Density /(g • cm^{-3})	Diameter /μm	Young modulus /MPa	Tensile strength /MPa	Elongation at break /%
Polypropylene	0.91	20	3 500	500	15.0
Basalt fiber	2.65	13	91−110	3 000−4 800	3.0−3.2
Palm fiber	1.28	0.2−0.3	800−1 900	87−166	19.0−21.0

(a) Frozen samples (b) Thawed samples

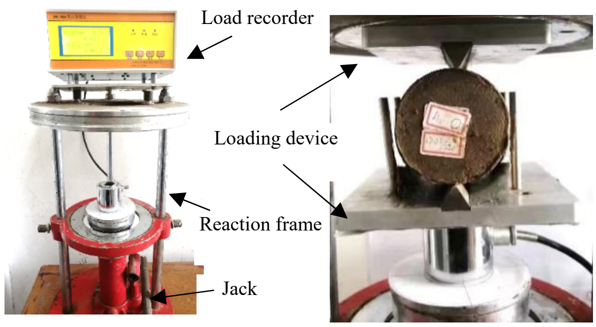
Fig. 1 The instrument of freeze-thaw test

2.2 Instrument

DR-2A freeze-thaw chamber, manufactured by Wuxi South China Experimental Instrument Co., Ltd., was employed for freeze-thaw test, as shown in Fig. 1. In recent 50 years, the mean and extreme minimum temperatures of Tianjin in winter are −10 ºC and −18 ºC, respectively, and the average temperature in spring is 18 ºC. Moreover, From the regulation of freeze-thaw test in "*Code for rock tests of hydroelectric and water conservancy engineering*" (DL/T 5368—2007)[20], the freeze-thaw test included 12 hours freezing at −20 ºC and 12 hours thawing at 20 ºC in one freeze-thaw cycle. The cycle was repeated for 1 to 15 times. Before the test, the samples were wrapped with plastic film to prevent water loss.

The unconfined compression tester was produced by Nanjing Soil Instrument Factory Co., Ltd. The proving ring coefficient was 31.8 N/0.01 mm, and the ultimate load was 10 kN. According to "*Test methods of soils for highway Engineering*" (JTG 3430—2020)[21], the test rate was set as 1 mm /min, and the axial deformation was collected at 0.5 mm intervals. The test was stopped until the reading of dynamometer reached the maximum, the deformation was basically stable, or the samples were damaged.

Considering the high strength of the lime-soil, its failure pattern is brittle failure. With reference to the Brazilian test device of rock, a splitting tensile test device for lime-soil was designed independently, as shown in Fig. 2. The test device consists of a pressurization system and a measuring system, including reaction frame, jack, load recorder, top and bottom loading device.



(a) Pressurization system and measuring systems (b) Loading device

Fig. 2 The instrument of splitting tensile test

The loading device was aligned and closely contact with the sample, as shown in Fig. 2(b). The load recorder reading was then cleared and the pressure was applied at a constant speed until the sample was damaged.

The equation of tensile strength is given:

$$f_{\mathrm{t}} = \frac{2P}{\pi l d} \tag{1}$$

where f_{t} is the tensile strength (MPa); P is the failure load (N); l is the sample height (mm); and d is the sample diameter (mm).

2.3 Sample preparation and test schemes

The sample was 61.8 mm in diameter and 125 mm in height, its water content was 16.8%, the dry density was 96% of the maximum dry density (1.71 g /cm^3), the lime content was 8%, and the fiber length was 19 mm (about 1/3 of the sample diameter)[17]. The samples were prepared by two-way static pressure method, and cured in the constant temperature and humidity curing box for 28 days after demolding. The test schemes are showed in Table 3.

Table 3 Test schemes

Test types	Freeze-thaw /times	Fiber types	Fiber rate /%
Unconfined compression test	0	Polypropylene fiber, basalt fiber, palm fiber	0, 0.1, 0.2, 0.3, 0.4, 0.5
Unconfined compression test	1−15	Polypropylene fiber	0, 0.1, 0.2, 0.3
		Basalt fiber	0, 0.1, 0.2, 0.3
		Palm fiber	0, 0.3, 0.4, 0.5
Splitting tensile test	0−15	Polypropylene fiber	0, 0.1, 0.2, 0.3

3 Optimum fiber rate by weight

3.1 Compressive strength

The compressive strengths of lime-soil and three types of fiber-lime-soils with fiber rate by weight are illustrated in Fig. 3.

The optimum fiber rates by weight of both polypropylene fiber-lime-soil and basalt fiber-lime-soil are 0.2%, and 0.4% for palm fiber-lime-soil. The maximum strength is 2 523 kPa and 2 055 kPa, respectively, and 1 842 kPa for palm fiber-lime-soil. All of them are higher than that of lime-soil (1 789 kPa).

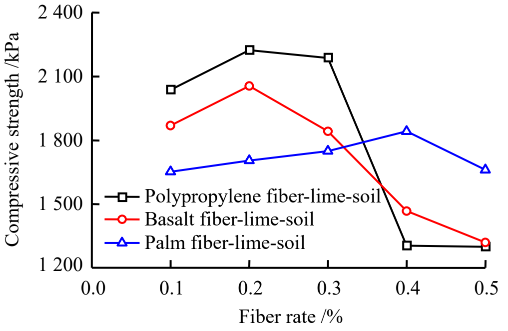


Fig. 3 Compressive strength of fiber-lime-soil vs. fiber rate

With the increase of fiber rate, the compressive strengths of the three types of fiber-lime-soils first increase, and then decrease. The friction and cohesion between the fiber and soil interface and the space constraint of the fiber on the soil limit the displacement of soil particles, and enhance the integrity and strength of the soil.

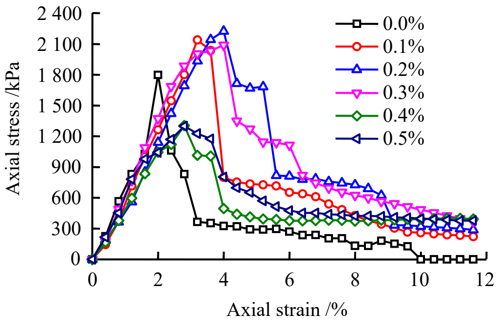
The strength of polypropylene fiber-lime-soil begins to decline as the fiber rate is greater than 0.2%, and it decreases significantly when the fiber rate exceeds 0.3%. Owing to relative light weight of polypropylene fiber, the number of fibers increases greatly with the increase of fiber rate. Excessive fibers agglomerate in the soil, forming a weak surface, damaging the soil integrity, which results in a significant decrease in soil strength, as shown in Fig. 4. Basalt fiber has poor dispersion, and the phenomenon of aggregation and stacking is more serious in soil. A large number of micro-cracks appear on the sample surface during the curing period when the fiber rate is greater than 0.2%, which leads to poor integrity of the sample, and the reinforcement effect is weaken. The diameter and density of palm fiber are large, then less fibers are in the sample under the same fiber rate condition, and the friction between fiber and soil is weak, so do as the space constraint of fibers on soil. Therefore, the compressive strength of palm fiber-lime-soil is low.

(a) Fiber rate 0.3% (b) Fiber rate 0.2%

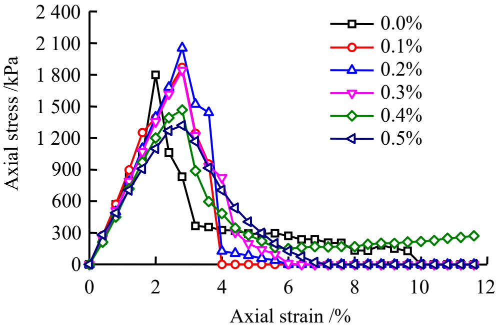
Fig. 4 Photos of fiber distribution in soil

3.2 Stress−strain curves

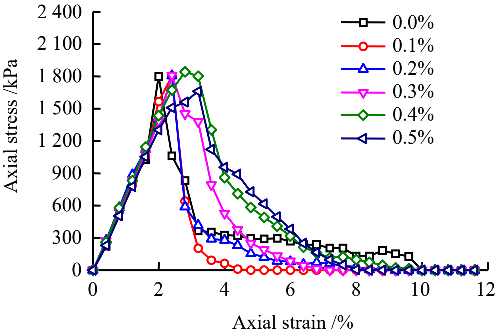
The stress−strain curves of polypropylene fiber, basalt fiber, and palm fiber-lime-soils with fiber rate are illustrated in Fig. 5.



(a) Polypropylene fiber



(b) Basalt fiber



(c) Palm fiber

Fig. 5 Stress−strain of fiber-lime-soil vs. fiber rate

With the increase of axial strain, the axial stress of lime-soil and three types of fiber-lime-soils first increase, then decrease, and finally tend to be stable.

When the fiber rates are 0.1%, 0.2% and 0.3%, the peak stresses of both polypropylene fiber-lime-soil and basalt fiber-lime-soil are greater than that of the lime-soil, and the peak stress reaches the maximum as the fiber rate is 0.2%. When the fiber rates are 0.4% and 0.5%, the peak stresses of both are less than that of the lime-soil. The peak stress difference of palm fiber-lime-soil is smaller at the 5 fiber rates. When the fiber rates are 0.1%, 0.2%, 0.3%, and 0.4%, the peak stress of palm fiber-lime-soil is higher than that of the lime-soil.

Figure 5 indicates that the strength of polypropylene fiber-lime-soil is the highest, followed by basalt fiber-lime-soil, and the strength of palm fiber-lime-soil is the lowest. The optimum fiber rates are 0.2%, 0.2%, and 0.4%, respectively.

4 Compressive properties under freeze-thaw cycles

4.1 Compressive strength

Figure 6 illustrates the compressive strength of polypropylene fiber, basalt fiber and palm fiber lime-soil with number of freeze-thaw cycles.

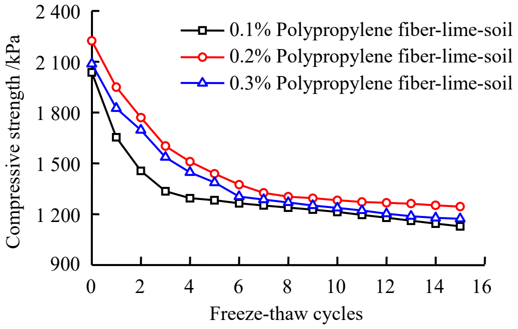
With the increase of freeze-thaw cycles, the compressive strength of lime-soil and fiber-lime-soil show the same phased downward trend. The decline is steep at 1 to 2 freeze-thaw cycles, and it becomes slowly at 3 to 10 freeze-thaw cycles. When 11 to 15 freeze-thaw cycles are subjected, the decline trend and soil strength tend to be stable.

The compressive strengths of polypropylene fiber, basalt fiber and palm fiber-lime-soil first increase and then decrease with the increase of fiber rate under freeze-thaw cycles, and the optimum fiber rates are 0.2%, 0.2%, and 0.4%, respectively, which is the same as that of soil without freezing and thawing. It indicates that freeze-thaw cycle has little effect on the relationship between fiber rate and soil strength.

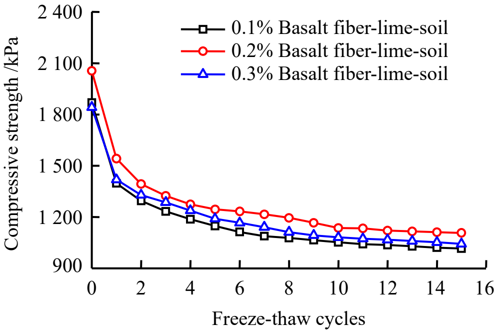
Compared with the lime-soil, the strength of fiber-lime-soil decreases relatively small, indicating that the fiber improves the freeze-thaw resistance of the lime-soil. The strength of the lime-soil decreases by 27.8% after 1 freeze-thaw cycle, and the strengths of three types of fiber-lime-soils decrease by 15.3%, 25.0%, and 19.8%, respectively. After 10 freeze-thaw cycles, the strength of the lime-soil decreases by 50.3%, while the strengths of the three types of fiber-lime-soils decrease by 40.3%, 44.7%, and 45.1%, respectively. After 15 freeze-thaw cycles, the strength of lime-soil decreases by 52.2%, while the strengths of three types of fiber-lime-soils decrease by 41.3%, 46.1%, and 46.5%, respectively. Therefore, it can be inferred that the compressive strength and freeze-thaw resistance of polypropylene fiber-lime-soil are the best, followed by basalt fiber-lime-soil, and palm fiber-lime-soil is worst.

4.2 Stress−strain curves

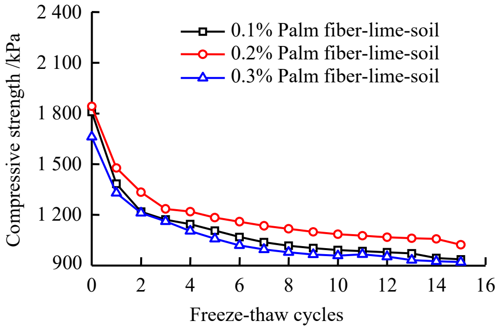
Due to space limitation, the stress−strain curves of



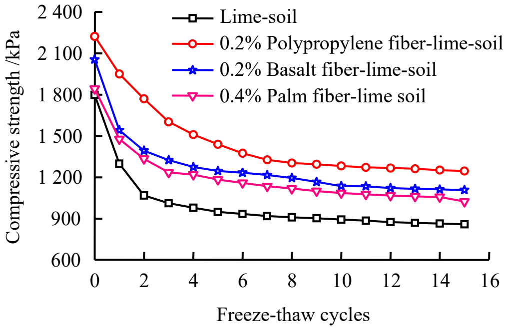
(a) Polypropylene fiber-lime-soil



(b) Basalt fiber-lime-soil



(c) Palm fiber-lime-soil



(d) Lime-soil and fiber-lime-soil

Fig. 6 Compressive strength of fiber-lime-soil vs. number of freeze-thaw cycles

lime-soil and three types of fiber-lime-soils at 0, 1, 7, 11 and 15 freeze-thaw cycles are presented according to the freeze-thaw stages, as shown in Figs. 7−10.

With the increase of freeze-thaw cycles, the peak stresses of the three types of fiber-lime-soils decrease, and the trends of stress−strain curves are basically the same strain softening types. The brittleness of lime-soil is rather great, while it is weaken in the fiber-lime-soil.

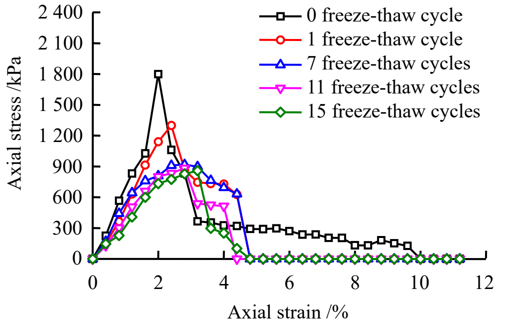
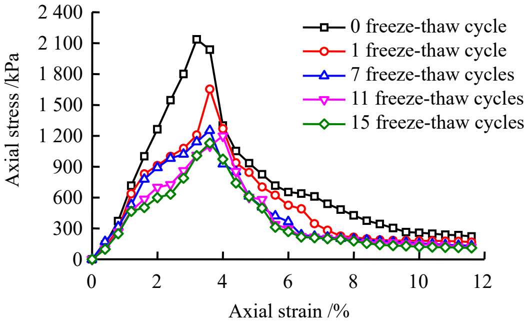
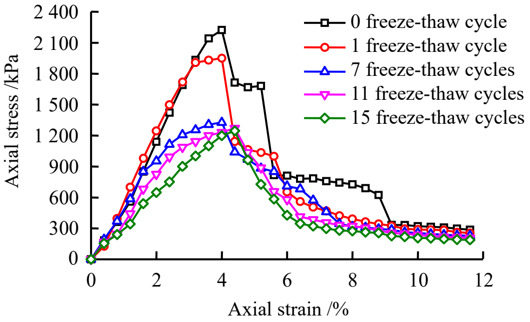


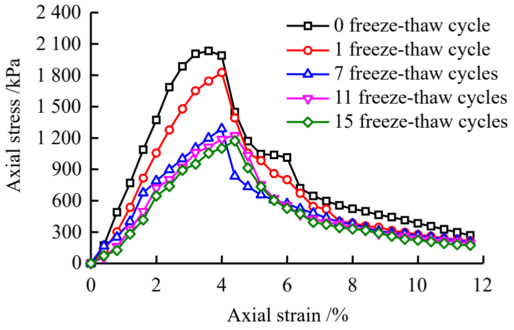
Fig. 7 Stress−strain curves of lime-soil under freeze-thaw cycles



(a) Fiber rate 0.1%



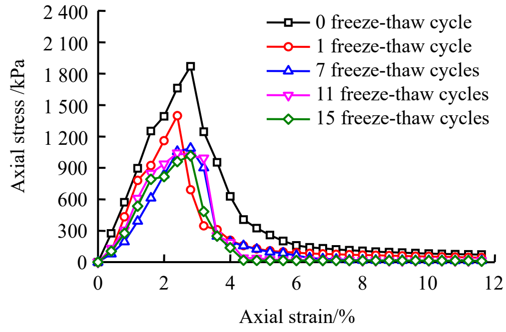
(b) Fiber rate 0.2%



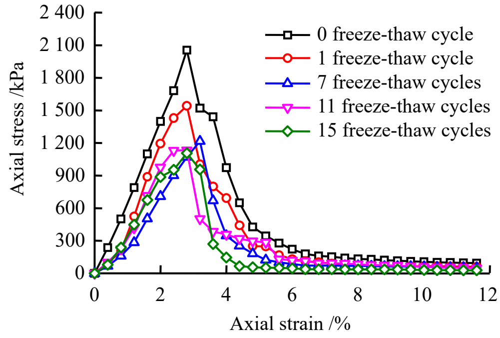
(c) Fiber rate 0.3%

Fig. 8 Stress−strain curves of polypropylene fiber-lime-soil under freeze-thaw cycles

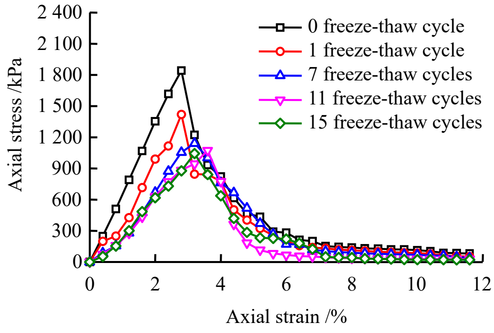
The fiber increases the failure strain of soil and enhances the deformation resistance of soil under freeze and thaw cycles. When the fiber rate is optimum, the failure strain of fiber-lime-soil is the largest. The failure strain of lime-soil is 2%, while it ranges from 3.6% to 4.4% for polypropylene fiber-lime-soil, 3.2% to 4.4% for basalt fiber-lime-soil, and 2.8% to 3.6% for palm fiber-lime-soil under the same freeze-thaw cycles and the optimum fiber rate. In view of the above, the deformation resistance of polypropylene fiber-lime-soil is the best under freeze-thaw cycles. In addition, it can be observed from the curves that the failure strain of fiber-lime-soil increases slightly with the increase of freeze-thaw cycles.



(a) Fiber rate 0.1%



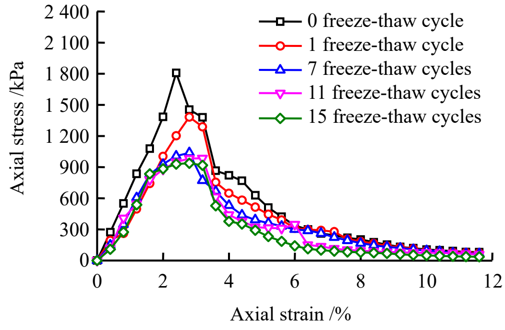
(b) Fiber rate 0.2%



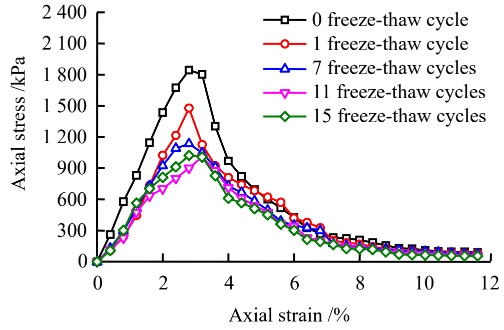
(c) Fiber rate 0.3%

Fig. 9 Stress−strain curves of basalt fiber-lime-soil under freeze-thaw cycles

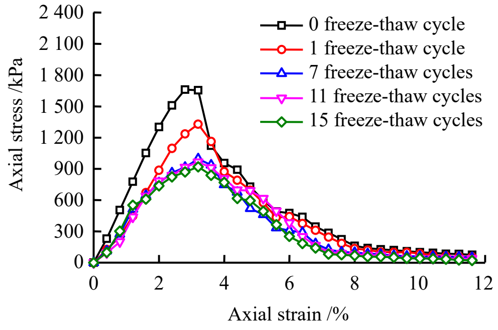
The friction and cohesion produced by fiber and soil particles limit the displacement of soil until the fiber is pulled off or pulled out under freeze and thaw cycles. A proper amount of fibers distribute evenly in the soil, forming a 3D spatial network structure, which can constrain the soil deformation effectively. The fiber enhances the compressive strength and deformation resistance of soil, and the freeze-thaw durability of soil is improved.



(a) Fiber rate 0.3%



(b) Fiber rate 0.4%



(c) Fiber rate 0.5%

Fig. 10 Stress−strain curves of palm fiber-lime-soil under freeze-thaw cycles

Comprehensively analyzing the compressive strength and deformation resistance of soil, and comparing the freeze-thaw resistance of three types of fiber-lime-soils, it can be concluded that polypropylene fiber-lime-soil is the best, followed by basalt fiber-lime-soil, palm fiber-lime-soil is the worst, but all of them are better than the lime-soil. Polypropylene fiber has good dispersion and the lightest weight, the largest number of fibers in soil under the same fiber rate condition. Additionally, polypropylene fiber is easy to bend in the soil with many interlacing points. Then the friction between fiber and soil particles is the strongest, so do as the space constraint of fiber on soil.

5 Tensile properties under freeze-thaw cycles

5.1 Splitting tensile strength vs. fiber rate

The variation of splitting tensile strength of polypropylene fiber-lime-soil with fiber rate is plotted in Fig. 11.

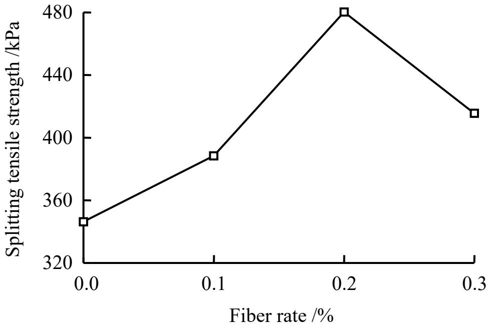


Fig. 11 Tensile strength of polypropylene fiber-lime-soil vs. fiber rate

The tensile strength of polypropylene fiber-lime-soil is significantly higher than that of the lime-soil under freeze-thaw cycles. The tensile strength of fiber-lime-soil first increases and then decreases with the increase of fiber rate. The splitting tensile strength reaches the maximum at 0.2% fiber rate, which is consistent with the result of compression test. If excessive fibers are added, it may distribute unevenly and agglomerate in the soil, then the soil compactness reduces, and the interaction between fiber and soil becomes weak. When the soil is stretched by external forces, stress concentration area is generated in the sample, resulting in low measured value of splitting tensile strength.

5.2 Splitting tensile strength vs. freeze-thaw cycles

The variation of splitting tensile strength of polypropylene fiber-lime-soil at different fiber rates with freeze-thaw cycles is shown in Fig. 12.

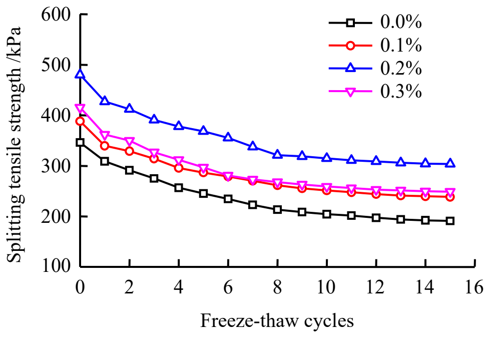


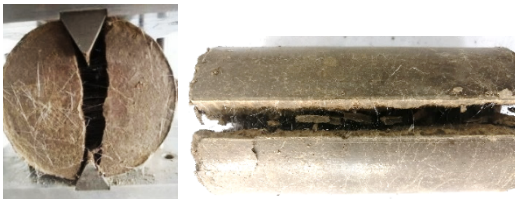
Fig. 12 Tensile strength of polypropylene fiber-lime-soil vs. freeze-thaw cycles

The strength of fiber-lime-soil is greater than that of the lime-soil at any freeze-thaw cycles. The tensile strength of fiber-lime-soil with 0.2% fiber rate is the highest, and its tensile strength decreases the least. The tensile strength decrease significantly after 1 freeze-thaw cycle, and the trend becomes slowly after 2 to 10 freeze-thaw cycles; When the freeze-thaw cycles exceeds 11 to 15 times, the tensile strength decreases slightly and tends to be stable, which is consistent with the results of unconfined compression test.

Figure 13 illustrates the tensile failure patterns of the lime-soil and polypropylene fiber-lime-soil after 10 freeze-thaw cycles.

Brittle failure pattern exists in the lime-soil sample without freezing and thawing, and the lime-soil is split into two uniform parts with rough fracture surface. Compared with the lime-soil, the fiber-lime-soil sample can not be split into two parts completely, and the phenomenon of “crack but not broken” appears. The failure surface is connected by countless fibers that plays a role of bridging. The fibers in Fig. 13(b) are clearly visible, and they are straightened gradually from the bending state until they are broken.

(a) Lime-soil



(b) Fiber-lime-soil

Fig. 13 Failure patterns of lime-soil and polypropylene fiber-lime-soil after 10 freeze-thaw cycles

6 Conclusions

(1) The strengths of three types of fiber-lime-soils are higher than that of lime-soil, and fiber-lime-soil improves the soil compressive strength. Whether under freeze-thaw cycle or not, the optimum fiber rates of polypropylene fiber-lime-soil and basalt fiber-lime-soil are 0.2%, and 0.4% for palm fiber-lime-soil.

(2) The fiber enhances the freeze-thaw resistance of soil. Both compressive strength and failure strain of

fiber-lime-soil are greater than those of the lime-soil under freeze-thaw cycles. The compressive strength of fiber-lime-soil demonstrates phased downward trend with the increase of freeze-thaw cycles.

(3) The tensile strength of polypropylene fiber-lime-soil is greater than that of the lime-soil under freeze-thaw cycles. With the increase of fiber rate, the tensile strength first increases and then decreases. The tensile strength of fiber-lime-soil also demonstrates phased downward trend.

(4) The freeze-thaw resistance of polypropylene fiber-lime-soil is superior to basalt fiber-lime-soil and palm fiber-lime-soil.

(5) The friction and cohesion produced by fiber and soil particles limit the displacement of soil particles. A proper amount of fiber distribute evenly in the soil, forming a 3D space network structure, which restrains soil damage effectively under freeze-thaw cycles, and the freeze-thaw durability of the soil is improved.

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