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Damage mechanism of soil-rock mixture after freeze-thaw cycles

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Abstract: As a widely distributed geological and engineering material, the soil-rock mixture always undergoes frequentative and short-term freeze-thaw cycles in some regions. Its internal structure is destroyed seriously, but the damage mechanism is not clear. Based on the damage factor, the damage research of properties of soil-rock mixture after different times of freeze-thaw cycles is investigated. Firstly, the size-distributed subgrade gravelly soil samples are prepared and undergo different times of freeze-thaw cycles periodically (0, 3, 6, 10), and indoor large-scale triaxial tests are completed. Secondly, the degradation degree of elastic modulus is considered as a damage factor, and applied to macro damage analysis of soil-rock mixture. Finally, the mesoscopic simulation of the experiments is achieved by PFC^{3D}, and the influence on strength between soil-rock particles caused by freeze-thaw cycles is analyzed. The results show that freeze-thaw cycles cause internal damage of samples by weakening the strength between mesoscopic soil-rock particles, and ultimately affect the macro properties. After freeze-thaw cycles, on the macro-scale, elastic modulus and shear strength of soil-rock mixture both decrease, and the decreasing degree is related to the times of cycles with the mathmatical quadratic form; on the meso-scale, freeze-thaw cycles mainly cause the degradation of the strength between soil-rock particles whose properties are different significantly.

Key words: soil-rock mixture; freeze-thaw cycle; large-scale triaxial test; strength between soil-rock particles

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1 Introduction

As a special engineering and geological material, soil-rock mixture is widely distributed in natural world, and always used in engineering such as subgrade padding. The special internal structure of soil-rock mixture makes it inhomogeneous, discontinuous, nonlinear, whose deformation and failure mechanism is more complicated than that of rock or soil [1]. According to internal structure of the soil-rock mixture, XU et al [2] defined the soil-rock mixture as one kind of extremely inhomogeneous and loose geotechnical material that composes of pore space, soil particles and rocks which have great strength and certain engineering scale. Because of the complexity of its composition, the theory researches of deformation and mechanical property of soil-rock mixture have not gotten into depth enough so far. Most researchers [3–8] investigated the deformation, mechanical property, permeability and acquire the

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excellent achievements. Previous studies mainly focus on deformation and failure mechanism of the normal soil-rock mixture, but there are rarely researches about soil-rock mixture after several freeze-thaw cycles. REGEHR et al [9] reviewed the disease of roadbed in permafrost regions based on a synthesis of literature findings. In some southern area of China, short-term freeze-thaw disasters occur more frequently, and the internal structure of soil-rock mixture is destroyed to some extent, whose mechanical properties are different from those in normal state. Thus, the related researches need to be carried out at once.

As for freeze-thaw cycle's influence, researches of the pure soil and rock are comprehensive so far, and the qualitative conclusions are agreed obviously that no matter soil or rock, their internal structure will show successive and cumulative damage after several times of freeze-thaw cycles, which cause the change of properties. But it is hard to observe change of internal particles in freeze-thaw cycles. KONG et al [10] showed the experimental results of the soil freeze-thaw process by using piezoceramic-based smart aggregate (SA) transducers. SUN et al [11] investigated the features of the change of the shear strength parameters of Lanzhou loess after freeze-thaw cycles. ZHANG et al [12] and ZHOU et al [13, 14] analyzed structure, physical and mechanical properties of soil under the effect of freeze-thaw cycles, and then believed that the damage of original structure resulted in all change of the properties. HE et al [15] explored the shear strength of fine-grained soil under influence of freeze-thaw cycles by triaxial tests, and then demonstrated the influence patterns of different factors (freeze-thaw cycle times, moisture content, compactness). LI et al [16] carried out the experiments of clayey soil under different freezing apparatus temperatures and freeze-thaw cycles.

Time of freeze-thaw cycles has significant effect on properties of rock or soil. With the times of the cycles increasing, the strength parameters rapidly decrease, and tend to be stable gradually when cycle time is beyond one certain value. LI et al [17] obtained the conclusion that porosity of rock increases with the increasing of freeze-thaw cycle time based on CT scanning technique. ZHENG et al [18] pointed that after freeze-thaw cycle, the liquid limits, plastic index and specific surface area all increased, and after 15 times, these parameters tended to be stable. LIU et al [19] carried out experiments and showed that the degradation of elastic modulus of the loess tended to be stable gradually after 5 times of freeze-thaw cycles. Similarly, XU et al [20] pointed that the damage of shear strength of the loess tended to be stable after 5 times of freeze-thaw cycles.

To sum up, although the researches on soil-rock mixture have been explored deeper and deeper, yet there are not enough achievements about the change of deformation and mechanical properties under the influence of freeze-thaw cycles. Because of its different components, as one kind of composite material, the properties of soil-rock mixture are complicated [21–26]. Based on the indoor large-scale triaxial experiment, the degradation behavior of soil-rock mixture after several times freeze-thaw cycles is analyzed in this paper, and furthermore combined with PFC and meso-damage theory, the relationship between macro-parameters and meso-parameters is explored, in order to supply help for predicting the parameters of soil-rock mixture after freeze-thaw cycles.

2 Indoor large-scale triaxial experiment

2.1 Experiment materials and design

Considering that large particles have important influence on macro-properties of the soil-rock mixture, large-scale triaxial experiment is very necessary and must be applied when analyzing the effect of freeze-thaw cycle times on soil-rock mixture. According to the previous research, the freeze-thaw influence is obvious in initial stage, and the change of the properties of soil-rock mixture tends to be stable after 6 cycles. The freeze-thaw cycle time is the control factor in the experiment, and is set up as 0, 3, 6, 10 in this paper. With reference to the graded gravel size standard of passenger railway's bed, the samples are composed of sandy clay, gravels and stone crumbles based on pro rata.

According to group's previous experimental data and investigation in some seasonal permafrost regions in China, the other parameters were set as follows: 45% of rock content, 6% of optimum moisture content, 92% of compactness degree. The grading curve of samples is shown in Figure 1.

The samples (45% of rock content) were

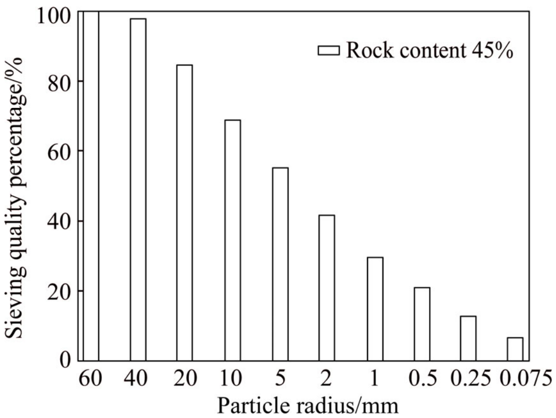

Figure 1 Particle grading curve of sample with rock content 45%

divided into four groups which undergo freeze-thaw cycles (0, 3, 6, 10) respectively, and each group included 3 parallel-groups (see in Table 1). Each sample was set up in self-made freeze-thaw equipment and undergoes cycles (every freezing period: 12 h, –11 °C; every thawing period: 12 h, 10 °C). The temperature setting was based on the weather data of some seasonal permafrost regions in southern areas in China which are always subjected to frequent freeze-thaw cycles in winter. Then the undrained shear tests were carried out under different confining pressures (50, 100, 200, 300 kPa) in large-scale dynamic and static triaxial apparatus: TAJ-2000 (see in Table 2 and Figure 2).

Table 1 Freeze-thaw cycle design sample list

Sample group	Parallel test sample tab	Cycle times
1#	1-1, 1-2, 1-3	0
2#	2-1, 2-2, 2-3	3
3#	3-1, 3-2, 3-3	6
4#	4-1, 4-2, 4-3	10

2.2 Experiment result analysis

For each confining pressure, one new sample was prepared, so there were all 48 samples. Through indoor triaxial test, 48 stress–strain curves were obtained including 48 samples with different freeze-thaw cycle times (0, 3, 6, 10) under 50, 100, 200, 300 kPa. According to different confining pressure, the samples' curves (tab: 1-2, 2-1, 3-1, 4-3) are shown in Figure 3.

The stress–strain curves in Figure 3 show that the soil-rock mixture with 45% rock content is strain softening material. The softening phenomenon is not obvious under high confining pressure, and gets more and more obvious with the

Table 2 TAJ-2000 dynamic-static triaxial apparatus parameters

Sample size/mm	Max axial load/kN	Max confining pressure/MPa	Axial deformation velocity/(mm·min^{-1})	Max axial displacement/mm	Volume change measure range/mL
Φ 300×600	2000	5.0	0.01–100	300	10000

Figure 2 Indoor triaxial freeze-thaw sample and equipment

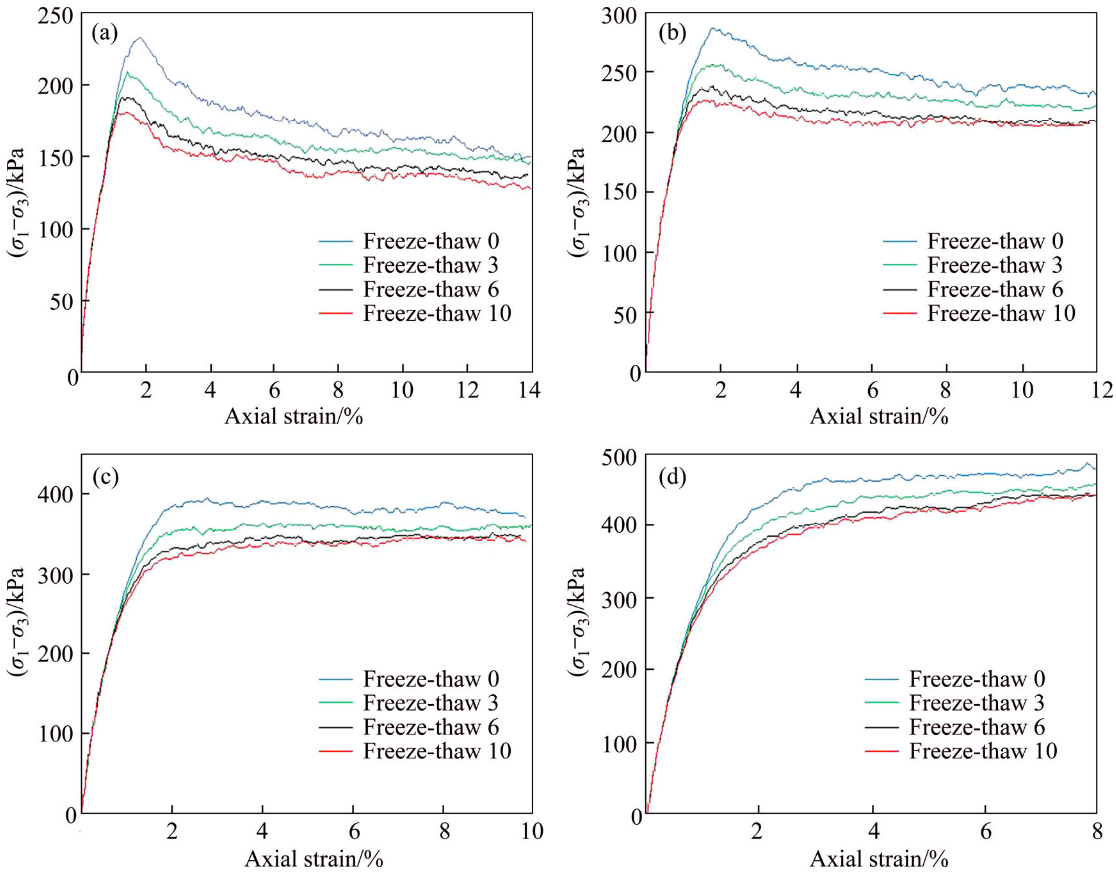

Figure 3 Stress–strain curves after different freeze-thaw cycles under different confining pressure: (a) 50 kPa; (b) 100 kPa; (c) 200 kPa; (d) 300 kPa

decreasing of confining pressure. It is because of high confining pressure's restraint influence. On the basis of experiment curve of soil-rock mixture, the shear failure can be divided into 4 periods: 1) particles' compaction initially; 2) elastic deformation; 3) plastic deformation; 4) yield stage. Meanwhile, under same freeze-thaw condition, the sample's static strength $(\sigma_1-\sigma_3)_f$ increases with increasing of confining pressure, and basically the relationship is linear. The static strength $(\sigma_1-\sigma_3)_f$ and elastic modulus E obtained from soil-rock mixture's stress-strain curve are shown in Tables 3 and 4 (regarding secant modulus as elastic modulus when axial strain approaches 1/3 strain at strength's peak).

2.3 Deformation and shear strength analysis under different times of freeze-thaw cycles

According to experimental data, freeze-thaw cycles cause the degradation of all kinds of mechanical parameters of soil-rock mixture, thus freeze-thaw cycles make properties of the material weakened. With the cycle times increasing, at initial stage, the degradation is obvious; at later stage, the effect becomes weaker gradually, which means when freeze-thaw cycle times is below 6, the soil-rock mixture's properties suffer from obvious weakening influence.

As shown in Figures 4 and 5, the decrement values of static strength and elastic modulus of soil-rock mixture increase with the increasing of cycle times, and the max value approaches 25% approximately. The correlation between decrement value and freeze-thaw times is quadratic basically, and the decrement trend is different when confining pressure is different. When confining pressure is low such as 50 kPa, the freeze-thaw decrement effect on static strength and elastic modulus is more significant. When confining pressure is high such as 300 kPa, the effect tends to be less, but can't be ignored still. Thus it can be seen that when higher confining pressure is acted on the soil-rock mixture sample, the pressure causes the compaction of the internal particles, which means the connections between particles are strengthened. The freeze-thaw cycle effect belongs to one kind of result which can

Table 3 Soil-rock mixture's static strength under different times of freeze-thaw cycles

Experiment Tab	Freeze-thaw cycle time	Static strength/kPa			
		50 kPa	100 kPa	200 kPa	300 kPa
1#	0	232	286	390	495
2#	3	208	260	363	462
3#	6	190	241	345	441
4#	10	180	231	334	429

Table 4 Soil-rock mixture's elastic modulus under different times of freeze-thaw cycles

Experiment Tab	Freeze-thaw cycle time	Elastic modulus/MPa				
		50 kPa	100 kPa	200 kPa	300 kPa	0 kPa
1#	0	11.72	14.67	20.00	25.38	9.33
2#	3	10.20	13.54	18.75	24.67	8.33
3#	6	9.18	12.75	17.90	23.69	7.61
4#	10	8.57	12.03	16.92	22.78	6.73

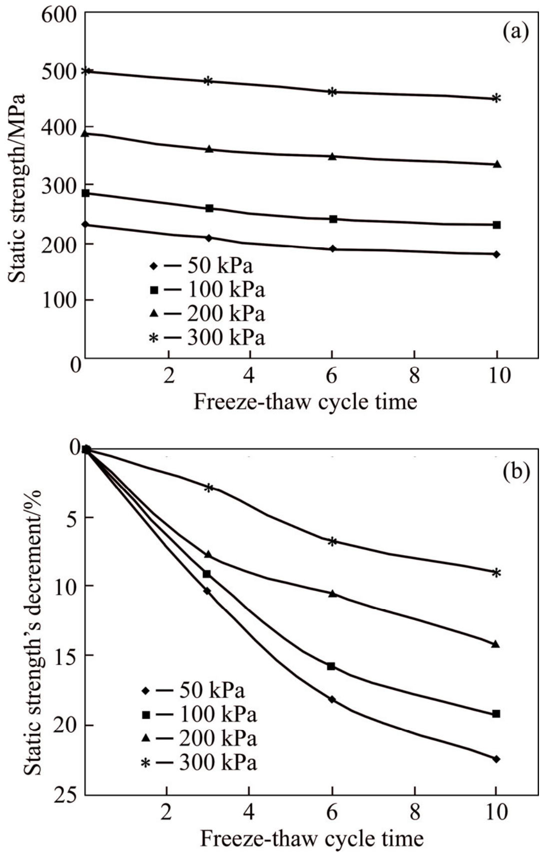

Figure 4 Static strength's decrement curves

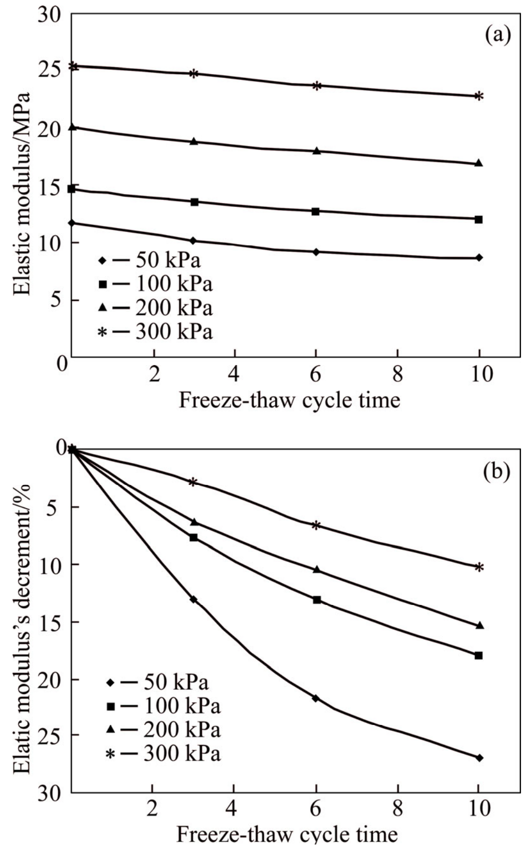

Figure 5 Elastic modulus's decrement curves

destroy or weaken connection of particle. So compared with more loose internal structure under low confining pressure, the samples under higher confining pressure need more cycles to make structure destroyed.

Based on the data of static strength under different confining pressures in the experiment, the shear strength parameters are calculated by using Mohr-Coulomb stress circle method (see in Table 5).

It can be seen from the change of cohesive force and frictional angle of samples after freeze-thaw cycles that both parameters decrease with the decreasing of cycle times, and the relationship is

Table 5 Shear strength parameters with different freeze-thaw cycle times

Parameter	Freeze-thaw 0	Freeze-thaw 3	Freeze-thaw 6	Freeze-thaw 10
C/kPa	36.66	35.52	34.56	34.01
Φ/(°)	42.91	36.65	32.41	30.40

quadratic. The result shows directly that freeze-thaw cycles weaken the connection and friction abilities between particles. The connections are destroyed. In fact, the freeze-thaw cycles directly cause that the soil and rock particles go away from each other. And it is the critical factor to change the C and Φ.

The soil-rock mixture self belongs to one kind of material whose connection is inferior and friction is obvious. After freeze-thaw cycles, connections between particles are destroyed to some extent, which makes the internal structure more loose, and it will be destroyed more easily when loaded. Compared with cohesive force, the influence on friction ability is more obvious. Because the cohesive force of normal soil-rock mixture ranges in low levels, the change of parameters is smaller.

The decrement value of cohesive force ΔC and friction $\Delta\varphi$ are defined as follows:

$$\Delta C = \left(1 - \frac{C_n}{C_0}\right) \times 100\% \quad (1)$$

$$\Delta\varphi = \left(1 - \frac{\varphi_n}{\varphi_0}\right) \times 100\% \quad (2)$$

Besides, in the formulas, C_0, φ_0 are cohesive force and friction angle of soil-rock mixture respectively at normal state. C_n and φ_n are cohesive force and friction angle of soil-rock mixture after freeze-thaw cycles. The relationships between decrement value and freeze-thaw cycle times for different parameters are matched by using Matlab software in Figures 6 and 7 as follows:

$$\Delta C = -0.05282 \times n^2 - 0.1648 \times n + 0.05912, \quad R=0.9987 \quad (3)$$

$$\Delta\varphi = -0.2859 \times n^2 - 0.392 \times n - 0.1798, \quad R=1 \quad (4)$$

According to the matching results, with the increasing of freeze-thaw cycle times, the decrement values of cohesive force and friction angle increase gradually, and the rate of decrement is smaller. At initial stage, the decrement of the properties of soil-rock mixture is obvious, while at later stage, the decrement is not obvious, which means that the properties of soil-rock mixture tend to be stable after some freeze-thaw cycles.

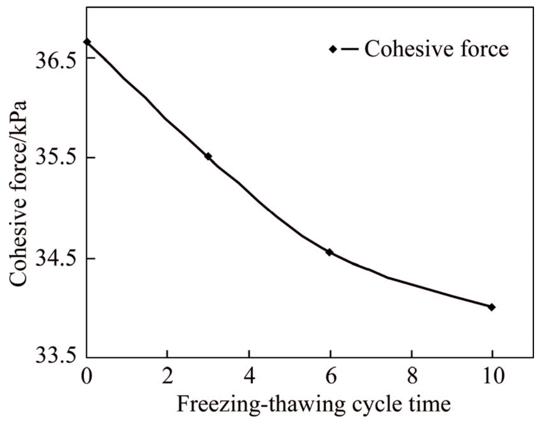

Figure 6 Cohesive force's decrement curve

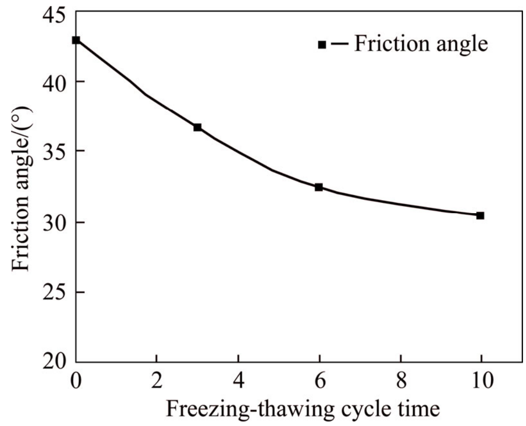

Figure 7 Friction angle's decrement curve

3 Freeze-thaw damage model

The special structure of soil-rock mixture decides its mechanical behaviors which are different with simple rock mass or soil. Its mechanical behaviors are combination of restraint, influence, coordination between rock particle and soil particle each other which have different sizes. When analyzing the deformation and mechanic properties, soil-rock mixture consists of enough rock whose influence can not be ignored. When mixture is loaded, the pore space between big rock particle and small soil particle is compacted and disappears, and particles start to move, which leads to the change of contact distribution between particles. Thus, the contacts between rock particles, between soil particles, between rock and soil particles are key to properties of soil-rock mixture. The mechanical properties of rock particle and soil particle vary extremely, which means that the contact layer between two kinds of particles is inevitably elastic mismatches. When mixture is effected by external factors, the strength and friction properties of the contact layer between soil and rock particles are the core factor which control failure of the mixture.

The big rock particle is surrounded by many different sized particles, and connects with each other (see Figure 8). It is supposed that the meso-structure of basic element of soil-rock mixture is composed of big rock particle, small soil particle and contact layer. Furthermore, soil particle and rock particle have different deformation and strength abilities, and contact layer consists of countless rock-soil particle contacts. According to internal structure of soil-rock mixture, rock-soil particle contact can be simplified into joint contact model, which is composed of stiffness and sliding spring model. Numbers of combined springs connect rock particle and soil particle.

K_n and K_s are the normal and tangential rigidity of joint contact, η_n and η_s are the normal and tangential damping of joint contact, μ is friction coefficient.

The sliding model (related with friction coefficient) of joint contact allows sliding of particles within the limits of shear strength, and the stiffness model (related with deformation stiffness at all directions) decides the stress–strain relationship. The failure of the joint contact is the essential reason of failure of soil-rock mixture. Similar with failure of macro-structure, there is normal tension strength and tangential shear strength at joint contact layer. When the stress of particle contact is beyond the strength, the joint contact is destroyed.

The freeze-thaw cycles weaken the whole structure of soil-rock mixture. Meanwhile, it can be believed that freeze-thaw cycles weaken the contact of internal particle and for the meso-contact structure, cause the damage of normal and tangential strength to some extent. As for damaged soil-rock mixture after freeze-thaw cycles, the deformation property (elastic modulus) is chosen as a damage factor. The decrement of the elastic modulus is the symbol of damage, and when freeze-thaw cycle time is 0, there is no damage, which means D=0:

$$D = 1 - \frac{E_n}{E_0} \tag{5}$$

In the formula, E_n is elastic modulus when freeze-thaw cycle time is n. Based on the triaxial test data, the decrement of elastic modulus with no confining pressure is chosen as the damage factor, and the relationship between freeze-thaw damage factor and cycle times is listed in Table 6 as follows.

The formula is matched by using Matlab software as follows:

$$D = -0.08842 \times n^2 + 3.642 \times n + 0.1529, \quad R=0.9991 \tag{6}$$

It can be seen from the formula that, with the increasing of freeze-thaw cycle time, the damage factor increases in the form of quadratic function. At initial stage, the damage factor increases faster,

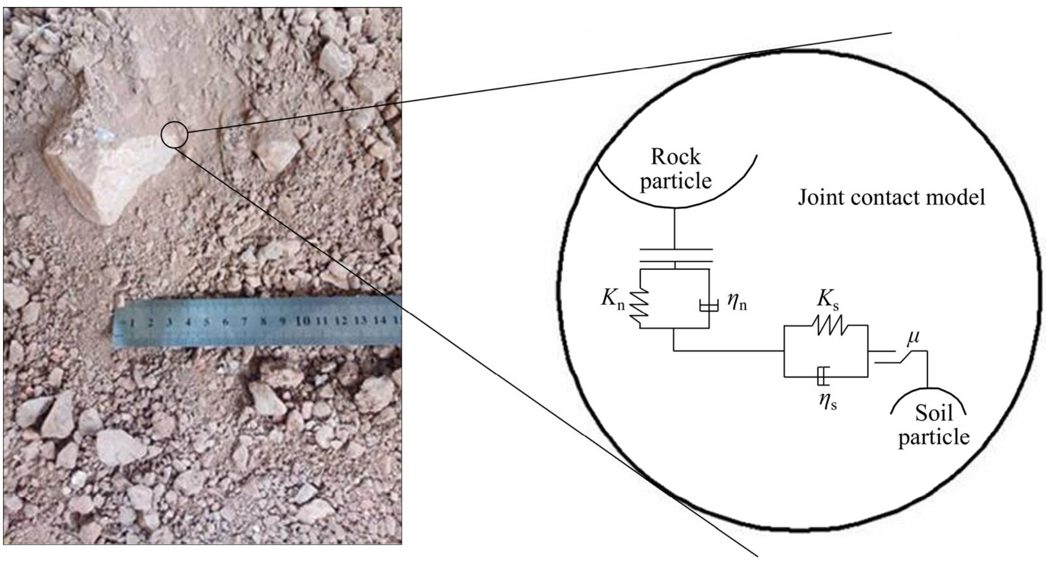

Figure 8 Contact model between rock particles and soil particles

Table 6 Relationship between freeze-thaw damage factor and cycle times

Cycle time	Damage factor/%
0	0
3	10.72
6	18.44
10	27.83

and at later stage, the rate tends to be slow, which means the damage factor will be stable after some cycles.

4 PFC numerical simulation

As a new-developed DEM software, PFC (Particle Flow Code) has been applied more and more widely in geological numerical simulation. PFC choses Newton motion equation as solving method, replaces elements with particles and can simulate large deformation. These advantages decide that PFC is very suitable to simulate the discrete soil-rock mixture. Combined with PFC software, the numerical indoor triaxial tests are simulated in the paper.

The size of the numerical sample is same as those in indoor triaxial tests, and all is Φ300 mm×600 mm cylinder sample whose particle size is set according to real distribution curve (see Figure 9). Because of the limit of computer calculation ability, the particle size is simplified: regard particles whose radius are below 5 mm as 5 mm particles; remain the rest particles as real distribution. Every sample contains 45198 particles. By writing indoor triaxial experiment serve and load program code, the confining pressure is simulated by setting side walls, and load is simulated by setting up and bottom wall up. Based on the existing PFC numerical simulation results (JIN et al [27], JIN et al [28], ZHU et al [29] and SHAO et al [30]) and indoor triaxial experiments data, the parameters of soil-rock mixture material and experiment equipment in the numerical simulation test are marked in Table 7 as follow.

Tension strength and shear strength of damage model in the paper can be simulated with joint contact bond model. Freeze-thaw cycle just causes the connection between particles weaker. Freeze-thaw effect on particles of samples can be explored through analyzing the decrement of normal bond strength and tangential bond strength in numerical model.

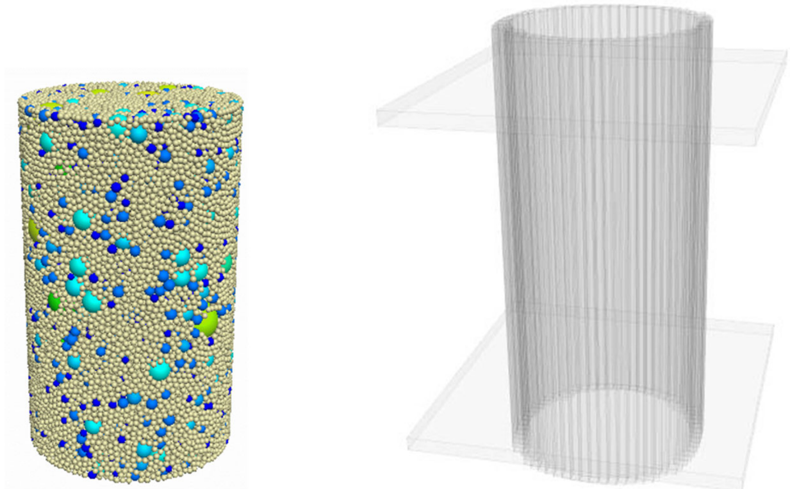
(a) (b)

Figure 9 PFC numerical simulation sample: (a) Triaxial numerical sample; (b) Triaxial restraint wall

Table 7 Parameters in PFC numerical simulation model

Particle parameter				Wall parameter				
Contact normal stiffness/ (kN·Pa^{-1})	Contact tangential stiffness/ (ks·Pa^{-1})	Friction factor	Damping	Load wall normal stiffness/ (kN·Pa^{-1})	Load wall tangential stiffness/ (ks·Pa^{-1})	Side wall normal stiffness/ (kN·Pa^{-1})	Side wall tangential stiffness/ (ks·Pa^{-1})	Friction factor
5×10^6	1×10^6	0.5	0.7	1×10^7	1×10^6	1×10^6	1×10^6	0.5

According to every stress–strain curve in indoor triaxial experiments, based on the parameters listed in Table 7, the stress–strain curves in numerical simulation can be matched by adjusting the value of normal and tangential bond strength. The bond strength is 0 for contacts between rock particles. And the contacts' bond strength between rock and soil particles is half of one between soil particles. For example, the stress–strain curves of the sample (marked 1-2) after different freeze-thaw cycles (time: 0, 3, 6, 10) are listed in Figure 10. The normal and tangential bond strength of all samples after different freeze-thaw cycles are listed in Table 8.

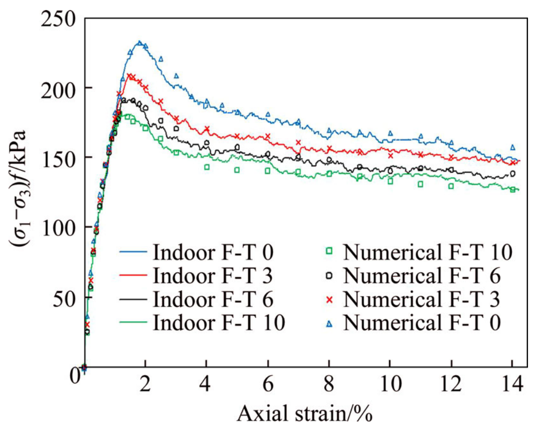

Figure 10 Comparison between indoor curves and numerical curves

In the freeze-thaw cycle damage model of indoor triaxial tests of soil-rock mixture, the damage factor is 0, 10.72%, 18.44%, 27.83%, respectively, when cycle time is 0, 3, 6, 10. Meanwhile, corresponding to contact layer damage in numerical simulation of soil-rock mixture, the decrement of the bond strength is 0, 10.90%, 19.90%, 30.81%, respectively, when cycle time is 0, 3, 6, 10. The decrements are similar closely, which means: in macro-scale, freeze-thaw cycles cause the damage in soil-rock mixture. More cycles, more damage, which leads to the decrement of elastic modulus and shear strength parameters of whole soil-rock mixture; in meso-scale, freeze-thaw cycles change the structure of internal particles, weaken all properties of contact layer between particles especially between soil and rock particles to some extent, which causes meso-structure weak and loose. The change in meso-scale finally results in the decrement in macro-scale. Comparing numerical simulation result with indoor triaxial experiments data, the decrement of contact layer in meso-structure is basically similar with damage factor which results from the decrement of elastic modulus in macro-scale, and the difference between them can be caused because of compaction of sample or big rock distribution indirectly.

The internal crack development states when triaxial test simulations (freeze-thaw cycle: 0, 3, 6, 10) are carried out are listed in Figure 11. The black areas are cracks of samples. Analyzing cross section of the sample, the figures show that the cracks increase with the increasing of cycle time, and when freeze-thaw cycle time gets to 6, the crack development is relatively obvious, which means the damage in the soil-rock mixture sample is considerable. Besides, most cracks are basically

Table 8 Normal and tangential bond strength of all samples in numerical simulation

Sample group	Freeze-thaw cycle time	Tab	Bond strength/Pa	Average value/Pa	Decrement value/%	Damage factor/%
		1-1	213			
1#	0	1-2	211	211	0	0
		1-3	209			
		2-1	185			
2#	3	2-2	188	188	10.90	10.72
		2-3	191			
		3-1	168			
3#	6	3-2	168	169	19.90	18.44
		3-3	171			
		4-1	146			
4#	10	4-2	148	146	30.81	27.83
		4-3	145			

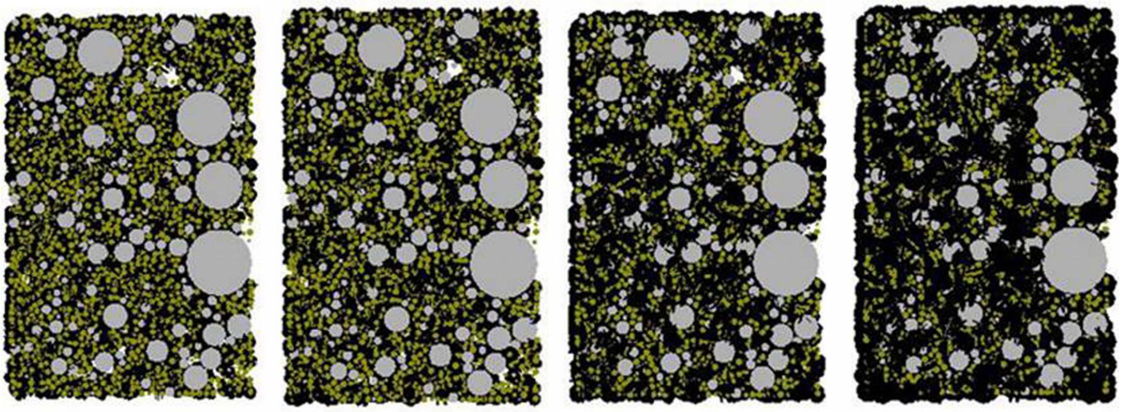

Figure 11 Internal crack development after different freeze-thaw cycles: (a) 0; (b) 3; (c) 6; (d) 10

located at contact layers between soil and rock particles, and the fracture zones appear there. It can be seen in Figure 11 that black cracks mainly distribute at contact layers in middle and bottom of sample where soil-rock particle contacts are more, which proves that freeze-thaw cycle damage obviously causes the decrement of the strength of soil-rock particle contact whose all properties are extremely different, and affects the failure behavior, furthermore, makes properties of soil-rock mixture weaker.

Coordination number is an important parameter to evaluate the distribution of contacts in PFC simulation, which is defined as the average contact number around alone particle. The smaller the coordination number, the less the contacts around the one single particle, which means the structure is destroyed more. In numerical simulation, through writing the data of coordination number of samples after different freeze-thaw cycles, when triaxial experiments are done, the coordination numbers of samples are 2.43, 2.20, 2.09, 2.03 in turn corresponding to freeze-thaw cycle time: 0, 3, 6, 10. The results show that with the increasing of freeze-thaw cycle time, the whole structure of sample is more loosen, and the properties of contact layer between particles are weaker, which leads to the failure of connections between particles and the decrease of contact number.

5 Conclusions

In order to analyze the most important external factor: cycle time in freeze-thaw researches of soil-rock mixture, the indoor large-scale triaxial experiments are carried out in this paper, and the change of macro-properties of the soil-rock mixture with different cycle times are investigated, then the freeze-thaw effects on meso-structure are analyzed, and meanwhile are simulated numerically and verified by using PFC software. The conclusions are as follows:

1) The stress–strain curves are similar when soil-rock mixture is under the normal state and freeze-thaw cycle state. When confining pressure is low, the soil-rock mixture belongs to strain softening material, and the phenomenon of strain softening is obvious after stepping into plastic state. When confining pressure is high, the phenomenon of strain softening exists still, but is not very outstanding. The elastic modulus ranges between ones of soil and rock.

2) After suffering from freeze-thaw cycles, the macro-properties of soil-rock mixture are weaker, and elastic modulus, cohesive force and friction angle decreases with cycle time increased in the quadratic function form, whose decrement trends are similar. When freeze-thaw cycle time is few, the decrement of properties of the material is obvious, and when cycles are enough, the rate of decrement gets slower, especially after 6.

3) Based on macro damage theory, the decrement of elastic modulus is chosen as the freeze-thaw damage factor of soil-rock mixture. The relationship function between cycle time and damage factor is matched according to indoor triaxial experiments data as follows: $D=-0.08842\times n^2+3.642\times n+0.1529$ ($R=0.9991$), when freeze-thaw cycle time is 0, 3, 6, 10, the damage factors of materials are 0, 10.44%, 18.72%, 27.83%,

respectively.

4) Analyzing the meso-structure of soil-rock mixture, the degradation of macro properties of soil-rock mixture is the expression of failure of meso-contacts between particles, furthermore, the freeze-thaw damage between soil particles and rock particles is more obvious because of the mismatch of elastic properties of two kinds of particles. Combined macro-analysis with meso-analysis, comparing indoor triaxial experiments data with numerical simulation results, meso-decrement of the properties of soil-rock mixture is basically consistent as meso-decrement of bond strength between particles, which proves that the decrement of macro-properties is related with the damage of meso-properties between particles.

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中文导读

冻融循环状态下土石混合体损伤机理

摘要：土石混合体作为一种广泛分布的工程地质材料，在很多地区遭受频繁的短期冻融循环。其内部结构受到严重损坏但破坏机理却不明晰。基于损伤因子，开展经历不同冻融次数下的土石混合体性质的损伤研究。首先，准备级配试样使其经历不同次数冻融循环（0, 3, 6, 10），并进行大型三轴试验。其次，将弹性模量衰减量视为损伤因子，应用于土石混合体宏观损伤研究。最后，利用 PFC^{3D} 模拟试验围观过程，分析冻融循环下土石颗粒间强度损伤影响。结果表明：冻融循环通过削弱土石颗粒间强度进而引起内部微观损伤，并最终影响宏观性质。冻融循环后，宏观上，土石混合体弹性模量与剪切模量均减小，且减小量与冻融次数为二次函数关系；微观上，冻融循环主要引起本身属性极大不同的土与石颗粒间强度的衰减。

关键词：土石混合体；冻融循环；大型三轴试验；土石颗粒间强度