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Li-yun TANG
School of Architecture and Civil Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi 710054, China

Xin WANG
School of Architecture and Civil Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi 710054, China, wangxindeli@163.com

Pei-yong QIU
Department of Civil, Geological and Mining Engineering, Polytechnique Montreal, Montreal H3C3A7, Canada

Long JIN
School of Architecture and Civil Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi 710054, China

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Study on shear performance of soil-rock mixture at the freezing-thawing interface in permafrost regions

TANG Li-yun[1], WANG Xin[1], QIU Pei-yong[2], JIN Long[3, 1]

1. School of Architecture and Civil Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi 710054, China
2. Department of Civil, Geological and Mining Engineering, Polytechnique Montreal, Montreal H3C3A7, Canada
3. CCCC First Highway Consultants Co., Ltd., Xi'an, Shaanxi 710000, China

Abstract: With the accelerated degradation of permafrost caused by global warming, the problem of slope stability of soil-rock mixture in permafrost regions has become increasingly prominent. To investigate the effects of different water contents and rock contents on the shear strength of soil-rock mixture at the freezing-thawing interface, direct shear tests were carried out on the freezing-thawing interface of soil-rock mixture, and the effects of water content (21%, 24%, 27%, 30%) and rock content (0, 10%, 20%, 30 %, 35%, 40%) on the shear strength of the interface were obtained. The test results show that the effect of water content on the shear strength of the freezing-thawing interface of soil-rock mixture can be divided into two stages: rapid decrease stage and slow decrease stage. The shear strength of the interface decreased rapidly as the water content increased from 21% to 27%, but the decreasing rate slowed down when the water content continued increasing to 30%, suggesting that the threshold value of the water content affecting the shear strength of freezing-thawing interface can be considered to be around 27%. The shear strength of freezing-thawing interface increased with rock content. The shear strength of freezing-thawing interface with the rock content of 10% significantly increased compared to that without rock, with the maximum increase of 33%. When the rock content exceeded 30%, the shear strength would increase rapidly, suggesting that the threshold value of the rock content affecting the shear strength of freezing-thawing interface can be considered to be around 30%. When the rock content was constant, the friction angle of interface gradually decreased with the increase of the water content, and the change tended to be stable after the water content reached 27%. However, the cohesive force at the interface decreased rapidly before the water content increased to 27%, and then decreased slowly. When the water content was constant, the friction angle at the interface increased with the increase of rock content especially when the rock content exceeded 30%. The cohesive force decreased first and then increased slowly with rock content ranging in 0%−30%, but the cohesive force increased rapidly and tended to be flat when the rock content exceeded 30%. When the rock content increased from 0% to 30%, the cohesion force first decreased slightly and then increased gently. After the rock content exceeded 30%, the cohesion force increased rapidly and then leveled off.

Keywords: soil-rock mixture; freezing-thawing interface; direct shear teat; permafrost

1 Introduction

Soil-rock mixture is different from the traditional homogeneous soil mass and cataclastic rock mass, and the main constituent material is the mixture of soil and block stone. As a special engineering geological body, it is characterized by the dual elements of permafrost and rock, showing extreme nonlinear and strong environmental dependence[1−2]. In the context of accelerated degradation of permafrost caused by global warming[3−5], the instability of various slopes on the Qinghai-Tibet Plateau has occurred frequently [6−11]. There are abundant ice crystals in the active layer of permafrost regions. As the active layer of permafrost regions in the slope thaws from the surface to the inside, the ice crystals gradually thaw into pore water. Since the permafrost beneath the frozen front is impermeable, the active layer of thawed soil-rock mixture is usually in a state of high water content. When the active layer of permafrost regions in the slope begins to thaw, a special freezing-thawing interface will be formed[12−14]. As a special engineering geological body[15−19], the physical and mechanical properties of soil-rock mixture are greatly complicated because the soil-rock mixture contains gravel and is at negative temperature[20−21]. The abrupt change of physical and mechanical properties of soil-rock mixture is usually at the freezing-thawing interface. The existence of this special interface and its properties are the key factors affecting the slope stability of soil-rock mixture in permafrost regions. Therefore, it is necessary to study the mechanical properties of the freezing-thawing interface of the soil-rock mixture with different water content and rock content.

At present, a lot of research work has been done on the shear strength of soil-rock mixture at the freezing-thawing interface. Through field exploration and research, Mcroberts et al.[22] demonstrated that thawing plays an important role in the failure of freezing-thawing interface

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First author: TANG Li-yun, female, born in 1977, PhD, Associate professor, mainly engaged in teaching and research work in permafrost and geotechnical engineering. E-mail: tangly@xust.edu.cn
Corresponding author: WANG Xin, male, born in 1994, Postgraduate student, majors in geotechnical engineering. E-mail: wangxindeli@163.com

of various types of landslides. Niu et al.[23] analyzed the stability of permafrost with high ice content under the ground ice surface (freezing-thawing interface) based on the project cases of thermal thawing and collapse in the permafrost region of Qinghai-Tibet Plateau, and put forward the measures to protect the permafrost from water and drainage. Through some experiments, Xu et al.[24] found that the soils at the freezing-thawing interface has obvious rheological properties, and the long-term shear strength index is smaller than the instantaneous strength index. Tong [25] and Toloukian et al.[26] found that the shear strength of soil at the freezing-thawing interface was higher than that of fully thawing soil through some field and laboratory tests. Jin et al.[12] presented that for low-angle landslides in the permafrost region of Qinghai-Tibet Plateau, the effect of stagnant water lubrication at the freezing-thawing interface of soil is one of the important causes of slope instability. Gao et al.[13] investigated the instability mechanism of natural slopes in permafrost regions through the direct shear test at the interface between ice and clay, silt and sand. The results showed that the increase of water during thawing period was the main reason for the slope instability of fine-grained soil. Chen et al.[27] carried out shear tests on the soil-rock mixture using a large direct shear apparatus with controlled low temperature and found that the shear strength of soils at the freezing-thawing interface was about 2 times that of soils with fully thawed. Gong et al.[28], Liu et al.[29], Xu et al.[30] conducted static overload tests on the slopes with five different rock contents and found that the rock content had an important impact on the development of the shear zone of slope. The failure mechanism of slope is a gradual transition from overall failure to local graded failure, and the threshold value of rock content of failure mechanism is within the range of 30%−53%. Ice bonds in the permafrost hold solid particles together and change the interaction between soil components, which has a great influence on the mechanical behaviour of soils. Haynes et al.[31] found that within a certain temperature range, the strength of shear failure surface was directly proportional to the negative temperature through direct shear tests. Through field tests, Takashi et al.[32] found that the water field at the freezing-thawing interface of slopes in permafrost regions presented the periodic changes with the external precipitation and solar radiation. Santander et al. [33], Tang et al.[34], Du et al. [35] believed that the temperature field, humidity field and stress field within the permafrost influence and interact with each other. Cheng et al.[36] verified the failure pattern of the soil slope at the freezing-thawing interface by using salt water to configure the freezing-thawing interface of soil slope.

Through the above analysis, it can be found that the water content and the rock content affect the mechanical properties of soil-rock mixture to a great extent, especially the shear strength. The soil-rock mixture is widely distributed in the whole permafrost or periglacial region and has a wide range of applications in engineering. However, most of the previous studies were limited to the shear strength of soil-rock mixture in non-permafrost regions or only consider the shear strength of soil at the freezing-thawing ice in seasonal frozen regions. There is a lack of basic research on the shear weak band of slope in permafrost regions, and the freezing-thawing interface of soil-rock mixture is rarely discussed in depth. Therefore, in this study, direct shear tests on the soil-rock mixture at the freezing-thawing interface with different moisture contents was carried out by using samples of soil-rock mixture at the freezing-thawing interface prepared by brine and pure water in order to explore the effect of water content and stone content on the mechanical parameters of soil-rock-mixture at the freezing-thawing interface. This study not only has important reference value for understanding the disaster mechanism of the soil-rock mixture slope in cold regions and targeted prevention and control measures, but also is a beneficial supplement to the research system of soil-rock mixture in the permafrost region.

2 Direct shear test

2.1 Sample preparation

The main materials used in the tests were clay, gravel, brine and purified water. To ensure the accuracy of water content, the clay was dried and then screened with a 2 mm sieve. The grain grading curves of soil and rock are shown in Fig. 1. The liquid limit and plastic limit of the fine-grained soil were 31.87% and 14.57%, respectively. In accordance with the requirements of '*Test Methods for Highway Engineering*' (JTG E40−2007) [37], the maximum size of rock should not exceed 1/4 of the height of the sample and 1/8 of the diameter of the sample. Therefore, the maximum size of gravel used in this study did not exceed 10 mm. In this study, the oversized rocks were removed by equivalent substitution method based on the size and gradation of rocks in a geological report of windy volcano. In the permafrost region near the wind volcano, water probes were arranged in the active layers of two soil slopes to monitor the sectional water. The results showed that the water content of soil in the slope during the thaw season had reached the liquid limit of clay. While in the same period, the measured water content of soil in the non-sliding active layer was about 20%. Therefore, in addition to selecting the soil's liquid limit of 30% as the maximum water content, and two water contents between 20% and 30%, i.e., 24% and 27%, were also used in this study.

First, the characteristic of the freezing point of saline water being lower than that of pure water was exploited. The size of each specimen was ϕ61.8 mm× 40 mm, and the upper and lower layers of specimens were made by the volume ratio of 1∶1. The upper layer of specimen adopted the salt water with the concentration of 1.5% to configure four different water contents. The lower layer of specimen was uniformly configured with pure water and the water content of specimen was 18%. The freezing temperature of brine water was about −4 ℃, determined by the test. The freezing point of the specimen prepared with brine water was about −5 ℃, slightly lower than the freezing temperature of brine water. In the test, the pure water was frozen at a freezing temperature of about 0 ℃, and all the samples were uniformly placed in the automatic incubator at −3 ℃ for 48 h. After freezing, the upper layer of the specimen was in a state of thawing at −3 ℃, while the lower layer of the specimen was in a state of freezing, thus achieving the state of freezing-thawing interface in the middle. Cheng et al. [36] and Ge[38] strictly controlled the shear position of the fixed interface in the shear test for freezing-thawing interface. For the control of freezing-thawing interface of samples in the test, firstly, the soil samples configured with pure water and saline water were required to be operated separately during the sample preparation process. There should be no cross contact between the two before making the freezing-thawing interface, and the sample preparation process took a short time, which should be completed within 1 to 2 min. After the sample preparation was completed, the specimen should be immediately placed in the low-temperature environment box for freezing. In the low temperature environment, the exchange of water molecules became slow, and the specimen could obtain obvious freezing-thawing interface and the height of freezing-thawing interface was within the required range after completing the freezing. At the same time, the shear tests were carried out in the walk-in low-temperature environment laboratory, which could better ensure that the freezing-thawing interface was not affected by the temperature, and the water migration did not cause obvious receding phenomenon of freezing-thawing interface.

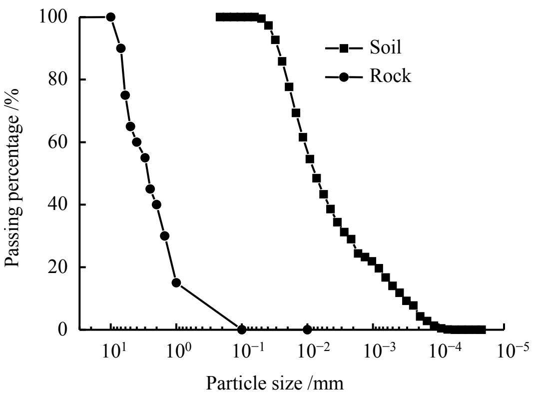


Fig. 1 Grain-size distribution curve

2.2 Test method

The shear tests on the soil-rock mixture at the freezing-thawing interface were conducted using the strain-controlled direct shear apparatus produced by Nanjing Soil Research Instrument Factory. The shear rate was selected as 0.8 mm/min, and the displacement data was automatically collected using the electronic dial indicator. The test environment was the walk-in cryogenic laboratory developed by Xi 'an University of Science and Technology. The indoor temperature was controlled at about −3 ℃, and the normal stresses applied were 50, 100, 200 and 300 kPa, respectively. In this study, 24 groups of different mixture samples were determined by considering the combination of four different water contents of 21%, 24%, 27% and 30%, and six different stone contents of 0%, 10%, 20%, 30%, 35% and 40%. The interface shear position was artificially fixed, so the shear occurred at the interface between thawing soil and frozen soil, and the specific test grouping conditions were shown in Table 1.

Table 1 Test conditions

No.	Water content /%	Normal pressure /kPa	Stone content /%
I	21	50	0，10，20，30，35，40
		100	0，10，20，30，35，40
		200	0，10，20，30，35，40
		300	0，10，20，30，35，40
II	24	50	0，10，20，30，35，40
		100	0，10，20，30，35，40
		200	0，10，20，30，35，40
		300	0，10，20，30，35，40
III	27	50	0，10，20，30，35，40
		100	0，10，20，30，35，40
		200	0，10，20，30，35，40
		300	0，10，20，30，35，40
IV	30	50	0，10，20，30，35，40
		100	0，10，20，30，35，40
		200	0，10，20，30，35，40
		300	0，10，20，30，35，40

The procedures of shear test were shown in Fig. 2: (1) Make soil-rock mixture samples with pure water under corresponding working conditions; (2) Continue to compact the soil sample configured with brine water on the sample with pure water; (3) Put the soil-rock mixture samples into the low-temperature test chamber and freeze them at −3 ℃ for 48 hours; (4) After the freezing-thawing interface was formed, the shear tests on the soil-rock mixture at the freezing-thawing interface under different normal stresses were carried out by filling the specimens in the low-temperature laboratory.

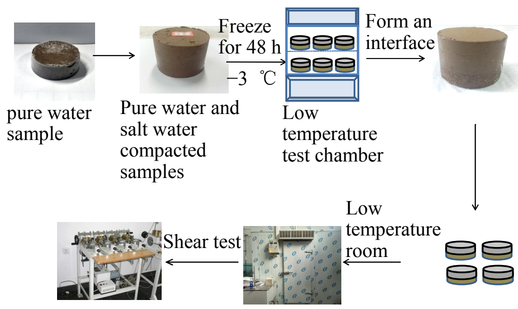


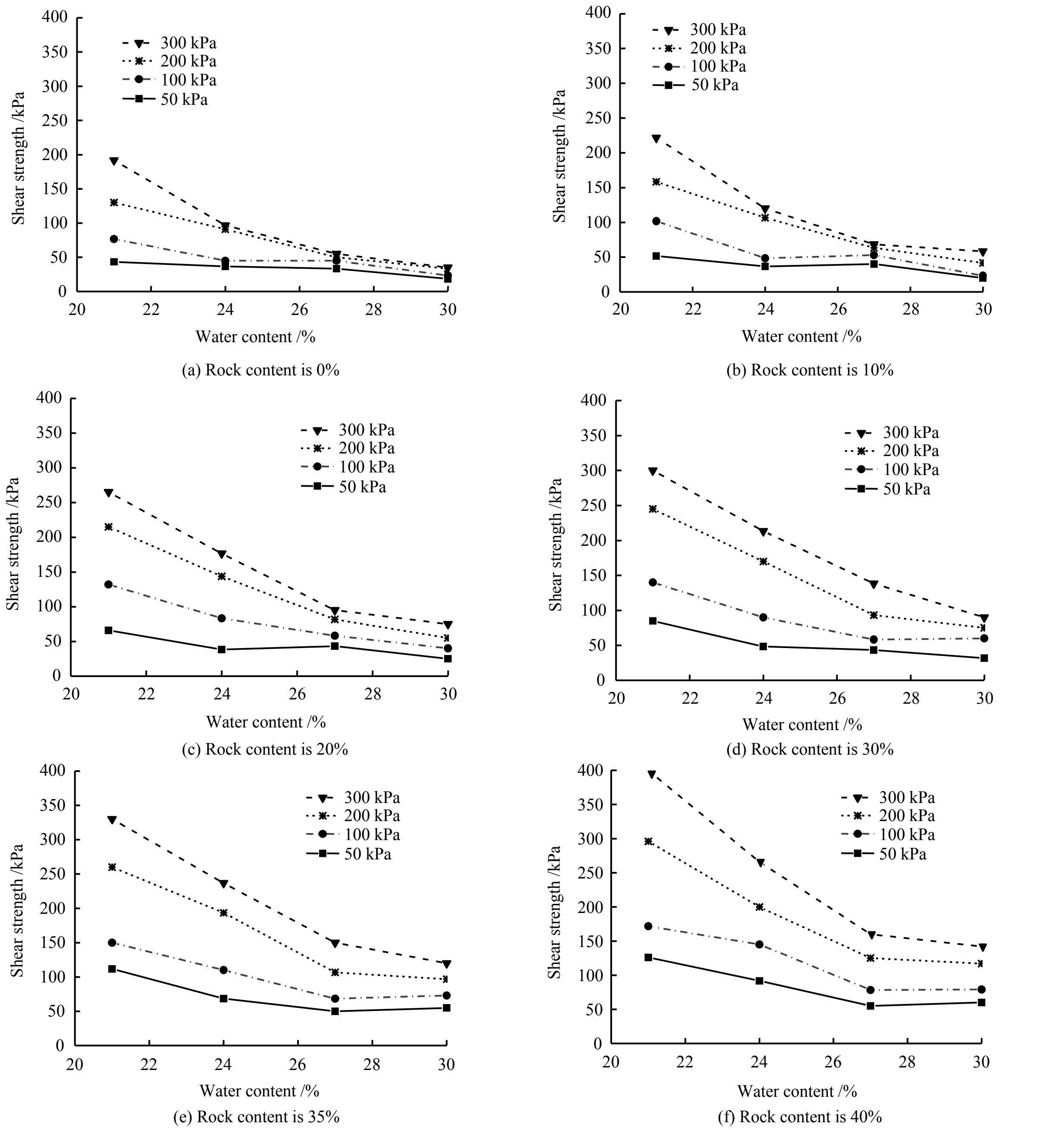
Fig. 2 Test procedure diagram of freezing-thawing interface of soil-rock mixture

3 Test results analysis

3.1 Variation of shear strength of soil-rock mixture at the freezing-thawing interface

3.1.1 Effect of water content on the shear strength of soil-rock mixture at the freezing-thawing interface

It can be seen from Fig. 3 that with the increase of water content, the influence of water content on the strength of soil-rock-mixture at the freezing-thawing interface presents two stages: rapid decline stage and slow decline stage. When the water content is between 21% and 27%, the strength of soil-rock-mixture at the freezing-thawing interface decreases rapidly. When the water content is between 27% and 30%, the shear strength continues to decline, but the rate of decline slowed down, that is, the threshold value of the influence of water content on the strength of soil-rock-mixture at the freezing-thawing interface is 27%. This phenomenon become more and more obvious with the increase of rock content. Especially in the case of high rock content (R > 30%), as the water content continues to increase, the curve shows a gentle state with little change in shear strength. The above indicates that the shear strength of soil-rock-mixture at the freezing-thawing interface is the most sensitive to the change of water content in the range of 21%−27% and the shear strength is easily affected by the change of water content within this range. However, when the water content is between 27% and 30%, the influence of water content on the strength of soil-rock-mixture at the freezing-thawing interface will decrease with the increase of rock content. The reason for this phenomenon



(a) Rock content is 0%
(b) Rock content is 10%
(c) Rock content is 20%
(d) Rock content is 30%
(e) Rock content is 35%
(f) Rock content is 40%

Fig. 3 Changing rule of shear strength of freezing-thawing interface under the influence of water content

is that the link between them is no longer significantly affected by the increase in water content as the soil particles gradually saturate. And this phenomenon is more obvious when the rock content is higher. The strength of soil-rock-mixture at the freezing-thawing interface is also greatly affected by normal stress, and this phenomenon decreases with the increase of water content. This is because the rock interlocked more tightly with each other at low water content. However, as the water content increases, the soil particles become soft, and the gravels are surrounded by water-rich particles to lubricate its surface. At the same time, the soft mud at the interface increases and then the pore water pressure increases as well. Therefore, the effect of normal stress on the shear strength of soil-rock-mixture at the freezing-thawing interface gradually decreases.

3.1.2 Effect of rock content on the shear strength of soil-rock mixture at the freezing-thawing interface

As can be seen from Fig. 4, the shear strength of soil-rock-mixture at the freezing-thawing interface increases with the increase of rock content. Especially when the stone content exceeds 30%, the strength increases obviously. This is because when the rock content in the mixture reaches the threshold, the effect of interlocking between the rocks become more prominent. Under the water content of 21%, the varied range of the interface strength with the normal stress under different rock contents is obviously greater than that under other water content. When the water content is 30%, the strength increases slowly as the rock content increases from 0% to 30%. This is due to the fact that the thawed soil in the upper layer of mixture is in a state of high water content, and the soil particles could not continue to provide soil cohesion. Only the interlocking between the gravels provides the shear strength, while the skeleton effect of the mixture with a small number of gravels is not obvious. At the interface of the mixture with low rock content ($R \leqslant 10\%$), the strength of the mixture at the interface with 10% rock content increases to some extent compared with that without rock content. With the increase of normal stress, this phenomenon would be more obvious, and the maximum increase reaches up to 33%. With the increase of normal stress, the higher the stone content of freezing-thawing interface, the more obvious the increase of shear strength. When the rock content was 40%, the change of normal stress had the greatest influence on shear strength. This indicates that with the increase of rock content, the normal stress plays an active role in the strength of soil-rock mixture at the freezing-thawing interface.

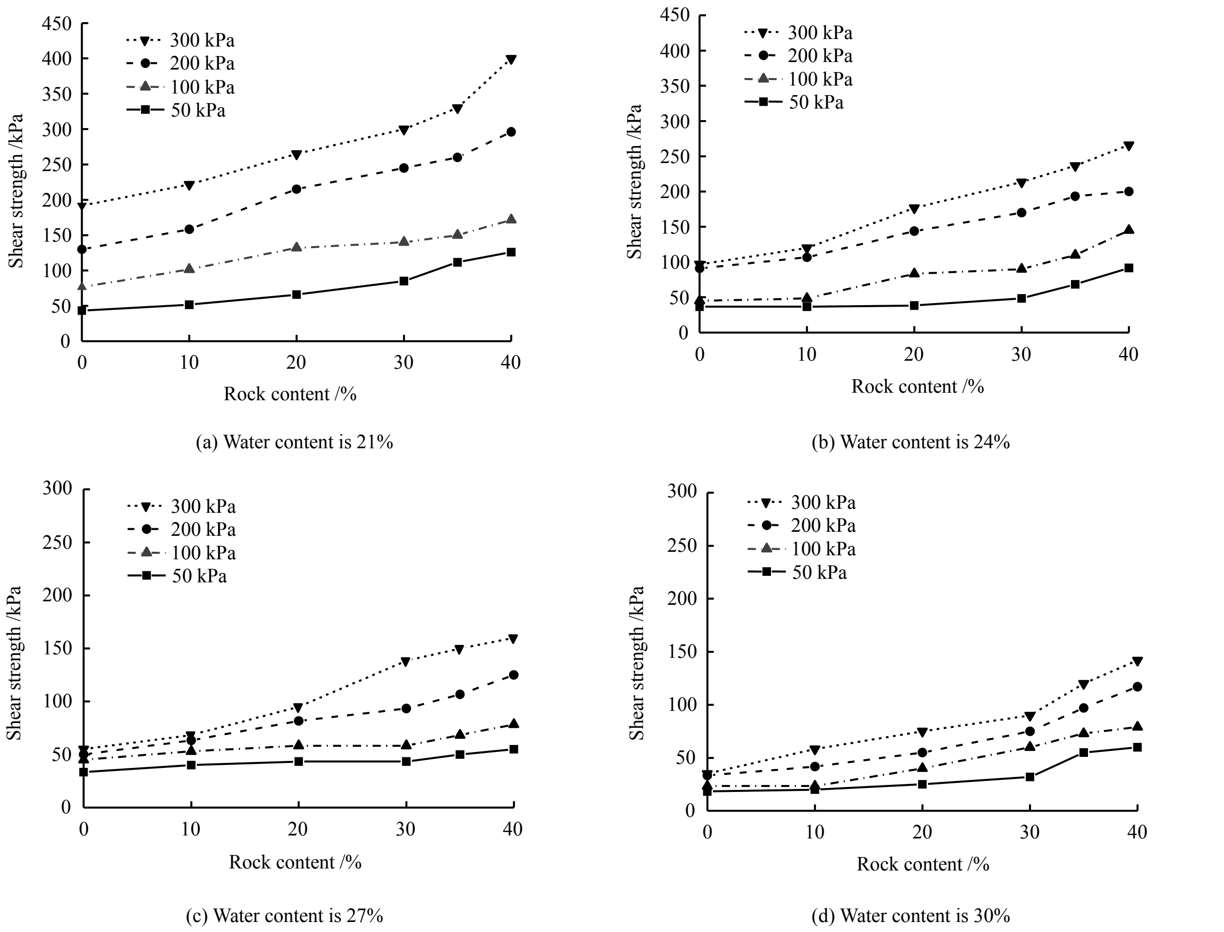


Fig. 4 Changing rule of shear strength of freezing-thawing interface under the influence of rock content

3.2 Variation laws of cohesion and friction angle of soil-rock mixture at the freezing-thawing interface

3.2.1 Effect of rock content on cohesion

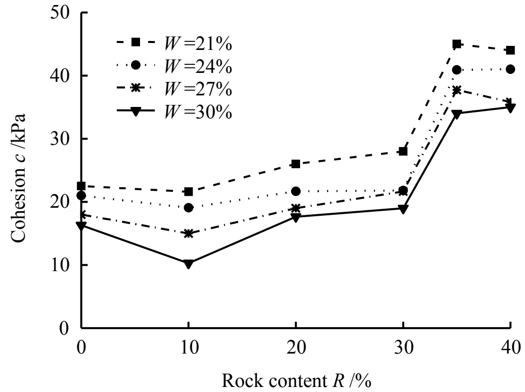
It can be seen from Fig. 5(a) that the cohesion tends to decrease under the condition of low rock content ($R \leqslant 10\%$). This is because the original cohesion is provided by the fine-grained soil, but with the increase of rock content, the fine-grained soil decreases, so the cohesion decreases. With the increase of stone content to medium stone content ($10\% < R \leqslant 30\%$), the overall cohesion changes little. However, when the mixture had high rock content ($R > 30\%$), the cohesion increases rapidly. It is believed that the gravels do not provide cohesion when the mixture at the surface with low and medium rock content, but when the rock content increases to 30%, the interlocking between rocks at the interface greatly increases, and the skeleton effect become obvious, so "false cohesion" occurs. When the rock content is greater than 35%, the cohesion changes slowly, indicating that the "false cohesion" could not increase continuously with the increase of water content instead of reaching a limit state.

3.2.2 Effect of water content on cohesion

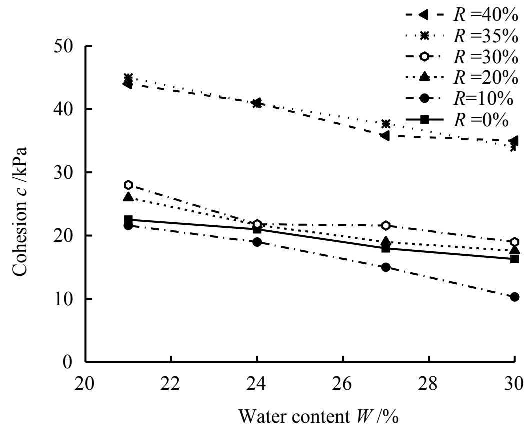
It can be seen from Fig. 5(b) that the cohesion of the mixture at the interface decreases linearly with the increase of water content. The cohesion curves of low rock content ($R \leqslant 10\%$), medium rock content ($10\% < R \leqslant 30\%$) and high rock content ($R > 30\%$) show obvious stratification. The cohesion of the mixture with high rock content is larger as a whole. The variation trend of the cohesion of the mixture with 35% and 40% rock contents is the same, and their curves have great similarity. Compared to the mixture with high rock content, water content has greater influence on the cohesion at the interface of the mixture with low and medium rock content because the proportion of fine-grained soil in the mixture with medium and low rock content is larger, and the fine-grained soil is more affected by water than the gravel. Therefore, when studying the influence of water content on the cohesion of the mixture at the interface, the rock content should be considered comprehensively.

3.2.3 Effect of rock content on friction angle

Figure 6(a) shows that the friction angle of the mixture at the interface presents an increasing trend with the increase of rock content. When the water contents are 27% and 30%, both variation trends of the friction angle of the mixture at the interface are similar as the stone content increases. When the water content is 27% and the rock content increases from 0% to 40%, the friction angle increases by 19.8°. When the water content is 30% and the rock content increases from 0% to 40%, the friction angle increases by 15.1°. Under the water contents of 21% and 24%, the friction angle of the mixture at the interface increases significantly as the rock content increases from 0% to 40%, especially

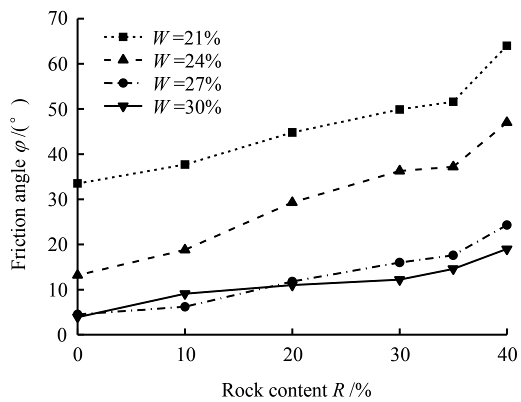


(a) Effects of rock content on the cohesion of interface

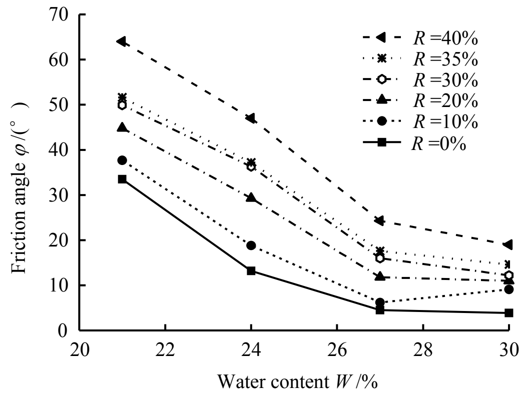


(b) Effects of water content on the cohesion of interface

Fig. 5 Effects of water content and rock content on the cohesion of interface



(a) Effect of rock content on the friction angle of interface



(b) Effects of water content on the friction angle of interface

Fig. 6 Effects of water content and rock content on the friction angle of interface

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when the rock content is high (R=35%). When the rock content is smaller than 30%, the friction angle of the mixture at the interface increases slowly under the water contents of 27% and 30%. When the rock content exceeds 30%, the friction angle increases rapidly, with the maximum increase up to 30%. This is because when the rock content of mixture exceeds the threshold, the interlocking effect between the rocks increases significantly, and the rock embedded in the lower layer of frozen soil could provide greater resistance. This phenomenon is more obvious under low water content.

3.2.4 Effect of water content on friction angle

Figure 6(b) manifests that the friction angle decreases with the increase of water content. When the water content ranges from 21% to 27%, the friction angle of the mixture at the interface decreases rapidly, among which the friction angle of the mixture with 40% rock content decreases by 62%, that of the mixture with 30% rock content decreases by 72%, and that of the mixture without rock only decreases by 29%, indicating that the water content has a great influence on the friction angle of the mixture at the interface. This is because with the increase of water content, the mud at the interface increases and the water film on the surface of the rock thickens, which reduces the interlocking between the rocks, and then resulting in the drop of friction angle. When the water content ranges from 27% to 30%, the friction angle decreases slowly and tends to be stable, among which the friction angle of the mixture with 40% rock decreases by 21%, that of the mixture with 30% rock decreases by 9.6% and that of the mixture with 20% rock decreases by 6.7%. The influence of water content on the friction angle of the mixture at the freezing-thawing interface decreases as the water content of mixture increases to the saturation state.

4 Analysis and discussion

4.1 Changing mechanism of the strength of the mixture at the freezing-thawing interface due to water content

The influence of water content change on the strength failure mechanism of the soil-rock mixture at the freezing-thawing interface is shown in Fig.7(a). With the increase of water content, the shear strength of the mixture at the interface decreases as a whole. In the process of increasing water content from 21% to 27%, the shear strength decreases rapidly. This is because the clay particles in the soil-rock mixture are small, with a large specific surface area and the mutual attraction between particles is strong. When the water content increases, the combined water film between the soil particles is damaged and the mutual attraction between the particles decreases. At the same time, in the process of sliding and cracking, the high water content of surrounding soils make the water film around the gravel thickened, which enhances the lubrication effect and weakens the interlocking force between its own gravel and the gravel below the freezing-thawing contact surface. The soft mud is also produced at the freezing-thawing surface with high moisture content, and the mixture at the freezing-thawing interface is supersaturated. Under the action of vertical stress, the pore water pressure increases, resulting in the extreme decrease in the overall shear strength. As shown in Fig.7(c), the threshold of water content of the soil-rock mixture at the freezing-thawing interface is 27%. In the process of increasing the water content from 27% to 30%, the shear strength of the mixture at the interface continues to decrease, but the trend gradually slows down because the effect of increased water on the reduced attraction between particles is gradually weakens. In practical engineering, the ice crystals on the surface of slope gradually thaw into water during the thawing period, which penetrates to the lower layer and accumulates near the soil layer at the interface. In the case of rainfall or extreme weather, heavy precipitation will accelerate the increase of pore water in soil layer and quickly complete the process of increasing the water content. At this time, the increasing water content of the mixture at the freezing-thawing interface in the slope results in the rapid decrease of shear strength in a short time, which rapidly leads to landslides. And excessive rainfall may even cause debris flow.

With the increase of water content, the cohesion of the soil-rock-mixture at the interface decreases rapidly at first and then levels off. This is because when the water content is smaller than 27%, the cohesion of soil particles in the soil-rock-mixture decreases rapidly with the increase of water content, and then the cohesion of soil-rock-mixture is greatly affected by the increase of water content. However, when the water content increases to 27%, the presence of gravel makes the change of cohesion tend to be flat, because the particles of fine-grained soil in the soil-rock mixture tend to be saturated gradually, and the cohesion provided by the fine-grained soil is not very obvious.

With the increase of water content, the friction angle presents the downward trend. This fact can be explained in two ways: On the one hand, due to the increase of water content, the soil grains become very soft. These water-rich particles are placed around the rock, lubricating the surface and reducing the friction resistance between the particles, consequently reducing the friction angle of the mixture at the interface. On the other hand, under high water content, the soil at the freezing-thawing interface become soft mud and pore water pressure increases, which reduce the interlocking force between coarse particles. However, when the water content is greater than 27%, the interface of soil-rock mixture is in a state of high water content, and the effect of increasing water content on the friction angle of the soil-rock mixture at the freezing-thawing interface is no longer obvious.

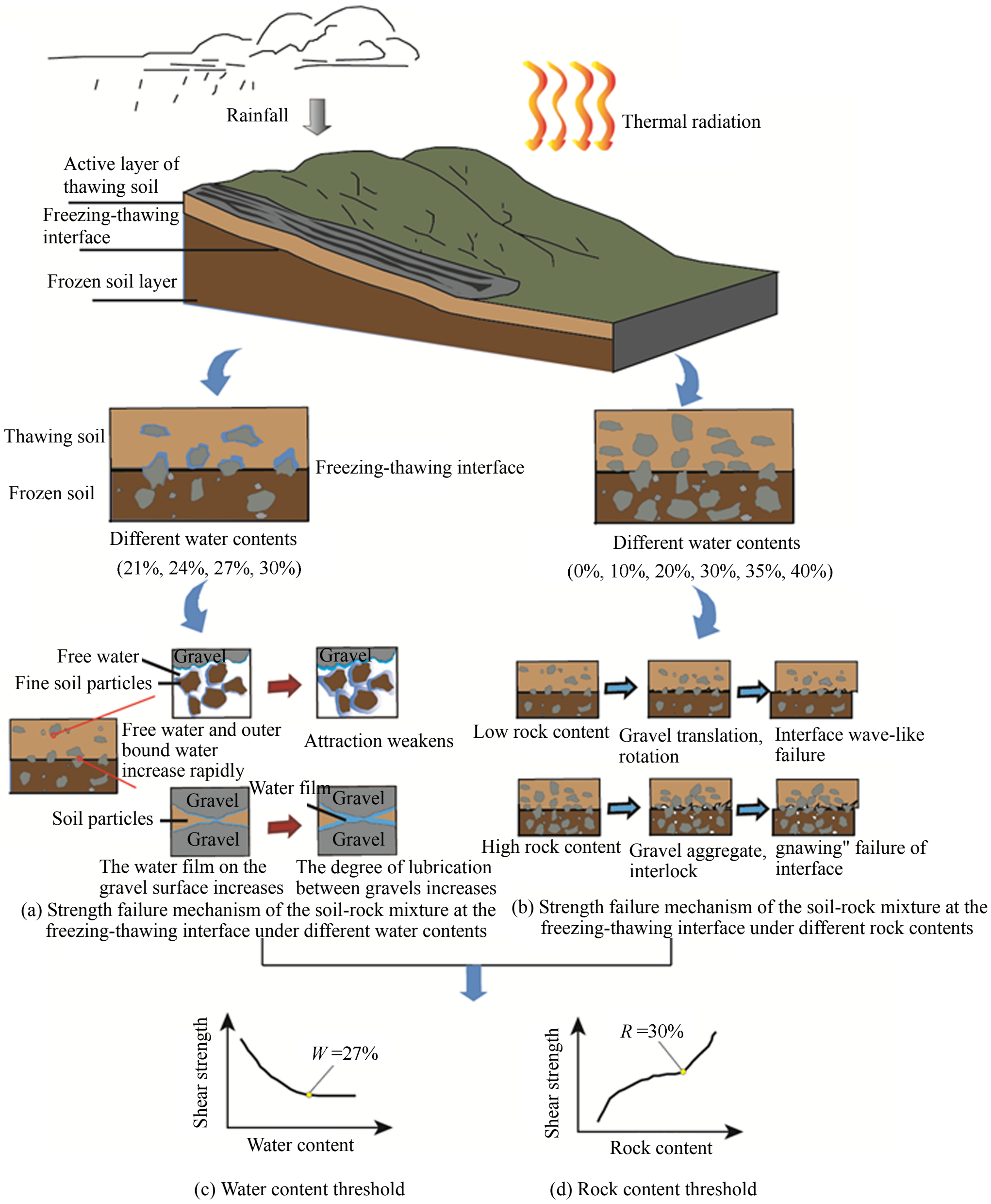

Fig. 7 Schematic diagram of the landslide mechanism of soil-rock mixture in the permafrost region

4.2 Changing mechanism of the strength of the mixture at the freezing-thawing interface due to rock content

The influence of rock content change on the strength failure mechanism of the soil-rock mixture at the freezing-thawing interface is shown in Fig. 7(b). The strength of the mixture at the interface with 10% rock content has a certain increase compared to that of the mixture at the interface without rock, and with the increase of normal stress, the increase of strength become obvious. This is because the rock in the lower layer of frozen soil is embedded in the stronger frozen soil. As the upper layer of thawing slips, the interlocking force between the rocks in the upper layer and lower layer increased, that is, a small number of rocks have an effect on strength. When the rock content is higher than 30%, the shear strength of the mixture is significantly higher than that of the mixture with low rock content. This is because when the rock content is high, especially under high stress, the rocks are more tightly locked into each other, and the skeleton effect of the mixture is more obvious. The threshold of rock content of the soil-rock mixture at the freezing-thawing interface is 30%, as shown in Fig. 7 (d). In the process of conducting direct shear tests on the contact surface of the mixture, some gravels embed in the frozen soil below the freezing-thawing interface and they must be bypassed during shearing. Therefore, the shear plane is a surface with some dislocations. The strength of the mixture at the freezing-thawing interface is not only affected by the interlocking force of gravels in the upper thawing soil and the lubrication of the ice at the interface, but also obtains a large interlocking force because some gravels embedded in the frozen soil below the freezing-thawing interface. When the rock content is low, the actual shear plane fluctuates along the main shear plane; when the rock content is high, the shear plane would show the "gnawing" failure.

For clayey soils, the shear strength is mainly provided by cohesion, while for soil-rock mixtures with higher rock content, the shear strength is mainly provided by friction angle. The friction angle of soil-rock mixture increases with the increase of rock content. When the rock content is higher than 30%, the density of mixture increases further, and the interlocking force between gravels starts to play a positive role rapidly, resulting in the "false cohesion", that is, part of the interlocking force turns into cohesion, which leads to the cohesion to increase sharply. When the rock content is higher than 35%, the fine-grained soil is not enough to fill the skeleton formed by rocks, and the rocks prevail. Thus the soil-rock mixture dramatically show the nature of gravels, and the friction angle of soil-rock mixture increases sharply.

From the above analysis, it can be seen that when the rock content is low, the rock is suspended in the medium mainly composed of soil. The distance between the rocks is large, and only a small number of rocks in the frozen soil at the lower layer of the freezing-thawing interface could provide "interlocking force". When the rock content is high, the frozen-thawed soil reaches the minimum void ratio, and there are a large number of gravels in the soil-rock mixture. In the mixture, the gravels at the lower layer of frozen soil have stronger shear strength, and the interaction with the gravels at the upper layer of thawed soil could bear most of the shear force. In the process of the interlocking and rolling of gravels, the soil is filled in the pores, which results the interlocking effect between the rocks become obvious, especially under high stress.

5 Conclusion

Aiming at the thawing process experienced by the soil-rock mixture slope in the permafrost region, the effect of rock content and high water content on the shear strength of the soil-rock mixture mixture at the freezing-thawing interface was investigated in this study through conducting the direct shear tests. The main conclusions are as follows:

(1) With the increase of water content, the influence of water content on the strength of soil-rock mixture at the freezing-thawing interface presented two stages: the rapid decline stage and the slow decline stage. In the process of increasing water content from 21% to 27%, the bonded water film between soil particles was damaged, which led to the decrease of mutual attraction and the thickening of the water film, and then enhancing the lubrication effect and weakening the interlocking force between the own rocks and the rocks at the lower layer of freezing-thawing interface. At the same time, the soft mud was produced at the freezing-thawing interface, and the pore water pressure would increase under vertical stress. The above causes an extreme reduction in the overall shear strength of soil-rock mixture at the freezing-thawing interface. As the water content continued to increase, the influence of water content on the strength was no longer obvious, that is, the threshold value of water content affecting the strength of soil-rock mixture at the freezing-thawing interface was about 27%.

(2) With the increase of rock content, the shear strength of soil-rock mixture at the freezing-thawing interface increases. The strength of mixture with rock content of 10% increases significantly compared to that of mixture without rock, with a maximum increase of 33%. When the rock content is higher than 30%, the shear strength of mixture increases rapidly because when the rock content is large, the rocks in the thawed soil would bite closely with the rocks in the lower frozen soil, especially under high stress. Under the action of high stress, the skeleton effect of mixture is more obvious, that is, the threshold value of rock content affecting the strength of soil-rock mixture at the freezing-thawing interface is about 30%.

(3) When the stone content is constant, the friction angle of the soil-rock mixture at the interface gradually decreases with the increase of water content, and changes slowly after the water content reaches 27%. While the cohesion of the soil-rock mixture at the interface decreases rapidly before the water content reaches 27% and then tends to decline slowly. When the water content is constant, the friction angle of the soil-rock mixture at the interface always increases with the increase of rock content, especially when the rock content is higher than 30%. When the rock content ranges from 0% to 30%, the cohesion first decreases slightly and then increases gently. After the rock content exceeds 30%, the cohesion increases rapidly and then leveled off.

(4) During the direct shear of the soil-rock mixture at the interface, some gravels embedded in the frozen soil below the freezing-thawing interface and they must be bypassed during shearing. Therefore, the real shear plane is not a smooth plane, but a surface with some dislocations. The strength of the mixture at the freezing-thawing interface is not only affected by the interlocking force of gravels in the upper thawing soil and the lubrication of the ice at the interface, but also obtains a large interlocking force because some gravels embedded in the frozen soil below the freezing-thawing interface. When the rock content is low, the actual shear plane is similar to a wave going up and down; when the rock content is high, the shear plane would show the "gnawing" failure.

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