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Experimental study on the evolution characteristics of cyclic frost heaving pressure of saturated fractured granite

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Abstract: The frost heaving pressure generated by water–ice phase change and volume expansion of saturated fractured rock mass in cold regions promote the initiation and expansion of new fractures, and lead to further damage and deterioration of fractured rock mass. To reveal the frost heaving pressure degradation mechanism of fractured rock mass subjected to multiple freeze–thaw cycles, the repeated frost heaving pressure monitoring test was carried out on saturated fractured granite with different macroscopic fractures under different freezing temperatures. The evolution characteristics of cyclic frost heaving pressure and the effect of crack size, freezing temperature and the number of freeze–thaw cycle on the frost heaving pressure of saturated fractured granite were analyzed. The results show that the evolution characteristics of frost heaving pressure in single freeze–thaw cycle is similar, which can be roughly divided into five stages. As the number of freeze–thaw cycles increases, the peak frost heaving pressure decreases exponentially, and the amplitude of peak frost heaving pressure drop increases. The peak frost heaving pressure increases linearly with the increase of crack length. The smaller the crack width, the earlier the frost heaving pressure appears in the freezing and thawing stages. The lower the freezing temperature, the earlier the frost heaving pressure appears. The peak frost heaving pressure increases linearly with the decrease of temperature, and the effect of freezing temperature on the frost heaving pressure weakens with the increase of freeze-thaw cycles. As the freezing temperature decreases, the effect of crack size on the peak frost heaving pressure becomes more significant. The research results can provide reference for the theoretical calculation and numerical analysis on frost heaving pressure of fractured rock masses in cold regions.

Keywords: frost heaving pressure; freeze–thaw cycles; fractured rock; evolution characteristics

1 Introduction

Since seasonally frozen soil and permanent frozen soil areas account for about 50% of the total land area, rock structures in mining and civil engineering often suffer from drastic temperature variations induced by seasonal alternations and day–night cycles in cold regions[1–3]. In particular, rock masses in cold regions undergo alternating water-ice phase change and water migration frequently, subjecting rock masses to repeated frost heaving pressure[4–5]. The long-term freeze–thaw (F–T) cycle causes gradual accumulation of expansion, shrinkage and cracking in rock mass and the deterioration of mechanical properties, and leads to geological disasters such as landslide and collapse[6]. The frost heaving pressure generated by the volume expansion after water–ice phase change is the main inducing factor of F–T damage and destruction of rock engineering. Therefore, the study on the evolution and deterioration mechanism of cyclic frost heaving pressure of saturated fractured rock masses has an important guiding significance for the prediction of long-term rock engineering stability and safe production in cold regions.

At present, many scholars have conducted research on the rock frost heaving pressure. In terms of laboratory tests, Winkler[7] conducted monitoring test of the frost heaving pressure generated by pore water under different freezing temperatures. It was pointed out that the freezing pressure of pore water can reach 61.0, 133.0 and 211.5 MPa at –5, –10, –20 ℃, respectively. Davidson et al.[8] measured the pressure caused by freezing expansion of transparent materials using photoelastic effect and found that the maximum frost heaving pressure of saturated cracks with a width of 1 mm was 1.1 MPa. Huang et al.[9] obtained the influence law of freezing temperature and fracture occurrence on frost heaving pressure by monitoring the frost heaving pressure and freezing temperature of rock-like specimens with fractures of different occurrences in single F–T cycle. Shan et al.[10] monitored the frost heaving pressure of fractured sandstone, and analyzed the effects of freezing temperature, fracture occurrence parameters and boundary conditions on the frost heaving pressure of fractured sandstone. In terms of theoretical research, Tan[11–12] and Murton[13–14] proposed a mathematical model of water migration in rocks, and quantitatively discussed the influence of water migration on rock fracture under freezing temperatures. Yan et al.[15] analyzed the influence of water–ice phase change on frost heaving propagation of micro-cracks and established the F–T damage constitutive model of elastic-plastic rock. Liu et al.[16] explained the frost heaving damage mechanism of fractured rock subjected to F–T cycle from the perspective of fracture mechanics, and established the relationship

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between joint length and frost heaving pressure. Tharp et al.[17] considered that cracks with an aspect ratio greater than 0.01 are prone to frost heaving propagation, and proposed a calculation method of stress intensity factor of frost heaving cracking. Liu et al.[18] established the calculation formula of unfrozen rock water content during freezing process from the perspective of elastic theory, and deduced the frost heaving deformation model of saturated rock. In terms of numerical simulation, Shen et al.[19] proposed an analytical formula for frost heaving load of low temperature fractured hard rock based on phase transition theory, elastoplastic theory and thermal theory. In addition, the internal temperature field and evolution law of frost heaving load of fractured hard rock during freezing are discussed by means of numerical simulation. Neaupane et al.[20] combined the temperature field, seepage field and stress field balance equations to derive the nonlinear rock constitutive equation subjected to F–T cycle and verified its accuracy by numerical simulation. Huang et al.[21] established the water-heat coupling model of fractured rock subjected to F-T cycle. In addition, the fracture network in construction of freezing method is constructed by simulation and the influence of fracture water seepage on fracture freezing circle in the freezing process was discussed.

Currently, there are relatively few research on the repeated frost heaving pressure evolution mechanism and frost heaving degradation mechanism of saturated fractured rock, and only limited theoretical research are reported. This paper presents repeated frost heaving pressure monitoring tests on granite specimens with different crack sizes subjected to different freezing temperatures. Through real-time monitoring of frost heaving pressure and temperature of the fractured specimen, the characteristics and evolution mechanism of repeated frost heaving pressure of fractured rock are investigated, and the characteristics of fractured rock subjected to long-term F–T cycle are revealed. The frost heaving degradation mechanism provides a reference for the research on failure and instability of rock engineering in cold regions.

2 Test introduction

2.1 Sample preparation

The test specimens used were drilled from the slope of the Beizhan open pit in Xinjiang, northwest China. The altitude of mining area is about 3 723 m and the minimum temperature can reach –40 ℃. As required by ISRM, the samples were manufactured into standard cylindrical samples with a diameter of 50 mm and a height of 100 mm. To study the effect of crack size on frost heaving pressure of fractured granite, the upper end surface of cylindrical specimen was manually cut along the diameter vertically, and the crack length was set to 30, 40 and 50 mm, respectively. The widths (W) are respectively set to 2, 3 and 4 mm, and the prepared typical specimens are shown in Table 1.

Table 1 Preparation of typical test samples

W /mm	Group 1 (L=30 mm)	Group 2 (L=40 mm)	Group 3 (L=50 mm)
2			
3			
4			

2.2 Test plan

Before the F–T test, sensor was fixed inside the specimen crack and a suitable thrust gauge was used to calibrate the accuracy of thin-film pressure sensor. To ensure the accuracy of thin-film pressure sensor and prolong the number of reuses, the circular sensing area at the end of the sensor was wrapped with cling film for waterproof treatment.

The specimens were put in purified water for 48 h for saturation treatment. To prevent the loss of water in the cracks before freezing, the two ends of the open cracks were sealed with waterproof tape before the freezing test, and then the cracks were filled with water using a syringe. Before each freezing progress, the water content inside the crack of specimen was observed, and a syringe was used to inject water into the crack to ensure that crack water surface was flat with the end face of specimen. The thin-film pressure sensor was placed in the crack, and the low temperature resistant temperature probe was placed on the surface of fractured granite to monitor the temperature change during the F–T cycle. The sensor placement position is shown in Fig.1, and the frost heaving pressure monitoring process is shown in Fig. 2.

The minimum temperature in Beizhan open pit mine is –40 ℃, and the measured monthly average temperature is shown in Fig. 3. Therefore, the freezing temperature was set to the specified temperature (–20, –30 ℃ and –40 ℃) and the thawing process was natural thawing at room temperature. The mechanics acquisition system, temperature monitoring device and strain acquisition system were turned on at the same time. By observing the change of specimen frost heaving pressure during the F–T cycle, it was found that when the specimen was frozen for 2.5 h, all the water in the crack was completely frozen into ice, and the collected data of frost heaving pressure remained unchanged for a long time. When the specimen was melted at room temperature, it was found that the internal ice was completely melted when the specimen was melted for 2.5 h, and the frost heaving pressure data remained unchanged after that. Therefore, each F–T cycle period was 5 h, as shown in Fig. 4.

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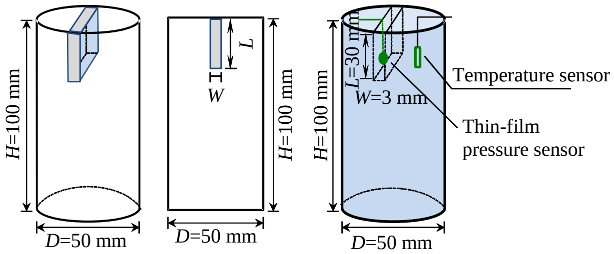


Fig. 1 Schematic diagram of sensor installation location

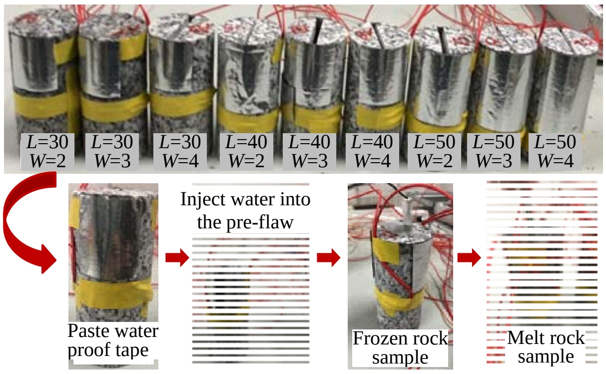


Fig. 2 Schematic of frost-heaving pressure monitoring (unit: mm)

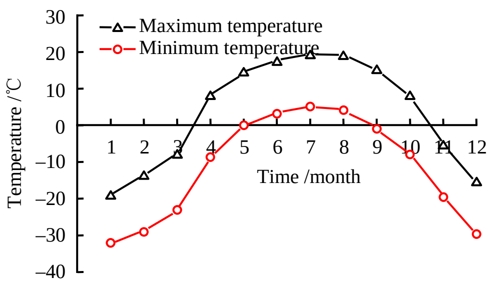


Fig. 3 Measured monthly average temperature in Beizhan mine

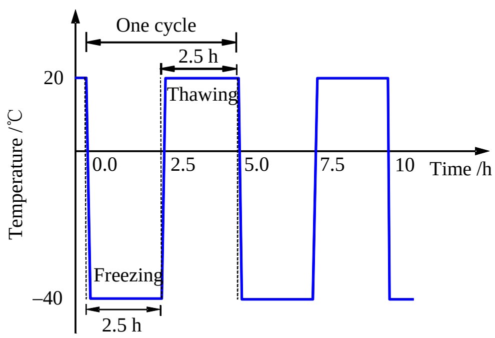


Fig. 4 Schematic diagram of freeze-thaw cycle

The total number of F–T cycle was set to 15 times, and the data of frost heaving pressure of each F–T cycle was collected and recorded. In addition, when the number of F–T cycle reached 1, 3, 5, 10, and 15, the ultrasonic wave velocity measurement of rock sample was carried out, respectively.

2.3 Test instruments

As shown in Fig. 5, the real-time frost heaving pressure monitoring system, the temperature acquisition system, the DW-45W300 cryopreservation box and the ZBL-U5200 ultrasonic detector were adopted to conduct the F–T treatments in this work. The real-time monitoring device for frost heaving pressure is mainly composed of thin-film pressure sensor and mechanical system acquisition card. The thickness of thin-film pressure sensor is about 0.2 mm, the minimum sensing area is 0.1 mm^2, the pressure sensing range is 0–1000 N, and the temperature response coefficient is ±0.36%/℃. The minimum temperature of cryopreservation box is –45 ℃, and the accuracy of temperature controller is 0.1 ℃. The measurement range of the temperature acquisition system is –200–80 ℃, and the measure- ment accuracy is ±0.3 ℃.

3 Test results

3.1 Evolution of frost heaving pressure

After the water in crack freezes into ice, a large frost heaving pressure is generated in the fractured rock due to water–ice phase change. Furthermore, the repeated frost heaving pressure in the F–T cycle causes the cracks to expand gradually. When the ice inside crack melts, more free water is present in the fractured rock, and the migration of free water in propagating crack causes the crack to further expand[22]. Therefore, frost heaving pressure is the fundamental driving force of rock fracture expansion subjected to F–T cycle, and is an important factor for the deteriora- tion of physical and mechanical properties of rock. The monitoring results of frost heaving pressure and surface temperature of rock sample at –20 ℃ with 40 mm crack length and 3 mm crack width during the fifth F–T cycle are plotted in Fig. 6.

The initiation, expansion and dissipation of frost heaving pressure are closely related to the freezing temperature. The evolution of frost heaving pressure of fractured rock and the rock surface temperature can be divided into five stages as shown in Fig. 6. Stage ①: At the initial stage of freezing, the rock surface temperature has not decreased to the freezing point. At this time, there is no water–ice phase change in the crack, and there is basically no frost heaving pressure in rock. Stage. ②: With further decrease of temperature to about –3 ℃, the free water at the upper end of opening crack first freezes into ice, causing part of free water under the crack to be sealed by the ice plug. The water–ice phase change inside the cracks occurs quickly, the frost heaving pressure increases suddenly, and the peak frost heaving pressure is about 4 MPa. Stage ③: With further decrease of rock temperature, the frost heaving pressure exceeds the tensile strength of rock matrix, and the frost heaving pressure drives the cracks to expand gradually. This will cause release of frost heaving pressure, but the rock matrix shrinks during the cooling process. Therefore, the combined effect makes the frost heaving pressure decrease slowly at this stage. Stage ④: As the rock surface temperature gradually rises but has not yet reached the thawing point, the rock matrix first experiences thermal expansion. The two walls of crack press inward on the ice in crack that has not melted in time, resulting in a second rise of frost heaving pressure. As the temperature rises to the thawing point, the ice begins to melt, and the water-ice phase change causes the ice to melt and shrink. Therefore, the two walls of the crack are no longer squeezed, and the frost heaving pressure gradually decreases. Stage ⑤: With the increase of rock surface temperature, the water-ice phase change in the crack is completed, and the frost heaving pressure in the crack gradually decreases until it disappears.

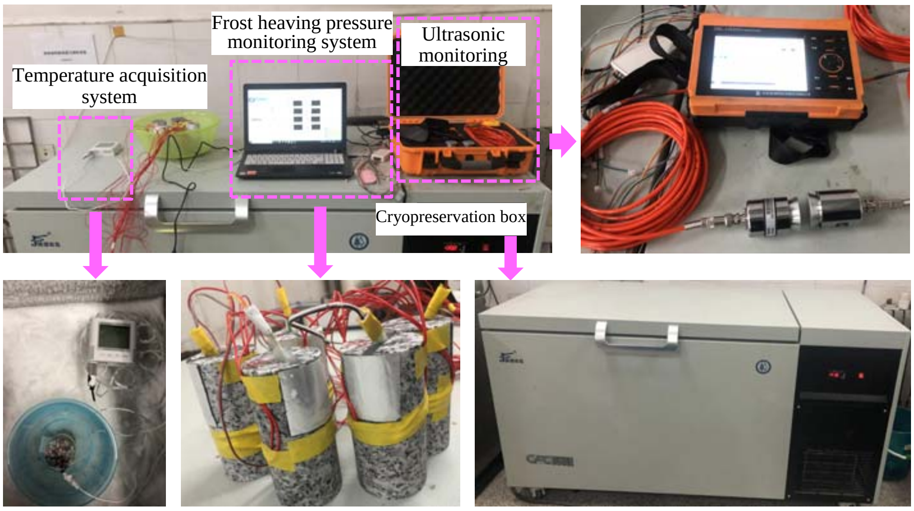


Fig. 5 Test instruments

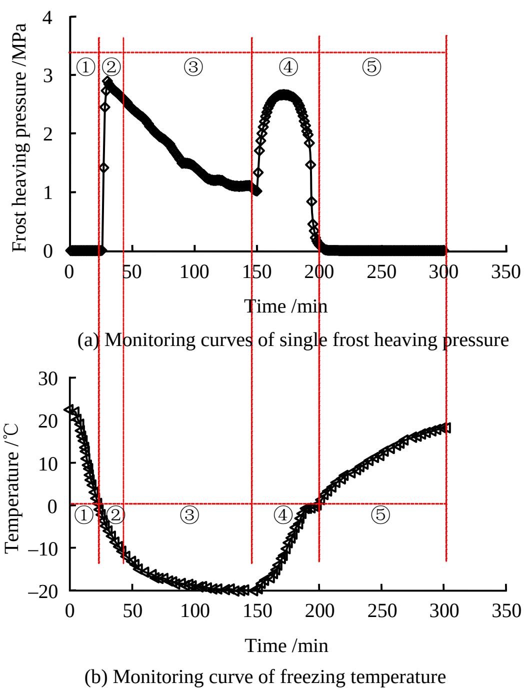
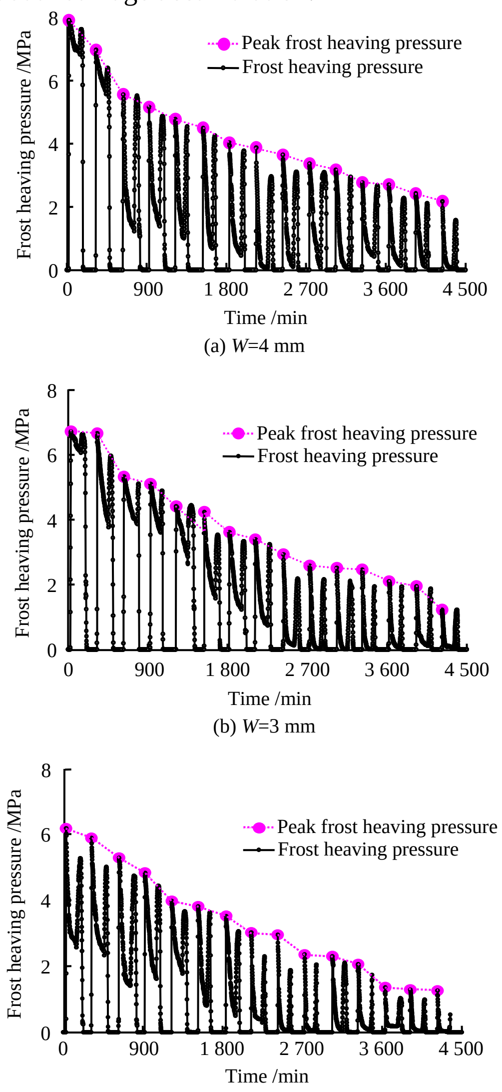


Fig. 6 Monitoring curves of single cycle frost-heaving pressure and freezing temperature

There are few studies on the evolution of frost heaving pressure during multiple F–T cycles. Due to space limitations, this paper selects the frost heaving pressure curve monitored by 15 F–T cycles of the specimen with a temperature of –40 ℃ and a crack length of 50 mm for analysis, as shown in Fig. 7.

The evolution characteristic of frost heaving pressure of fractured granite samples is consistent. It can be concluded from Fig. 7 that in the monitoring of the frost heaving pressure of multiple F–T cycles, the peak frost heaving pressure gradually decreases with increasing number of F–T cycles. When the crack length is 50 mm and the width is 4 mm, the peak frost heaving pressure of the first F–T cycle is about 10.75 MPa, and the peak frost heaving pressure of the 15th F–T cycle decreases to about 2.95 MPa, which is 72.5% less than that of the first F–T cycle. When the crack length is 50 mm and width is 3 mm, the peak frost heaving pressure of the first F–T cycle is about 9.13 MPa, and the peak frost heaving pressure of the 15th F–T cycle drops to about 1.66 MPa, the peak frost heaving force is reduced by 81.8% compared with the first F–T cycle. When the crack length is 50 mm and the width is 2 mm, the peak frost heaving pressure of the first F–T cycle is about 8.40 MPa, and the peak frost heaving pressure of the 15th F–T cycle decreases to about 1.40 MPa, which is 83.3% less than that of the first F–T cycle. With the increase of F–T cycles, the greater the drop after the frost heaving pressure reaches its peak. This is because in the early F–T cycle, the F–T damage of rock is small, the cracks driven by the frost heaving pressure are rarely expanded, and the release of frost heaving pressure is very small. As the increase of F–T cycles, crack fracture and propagation caused by frost heaving pressure in granites are significantly increased, and the release phenomenon of frost heaving pressure increases obviously. After the frost heaving pressure reaches its peak, the drop amplitude is larger, which also indicated that the degradation of rock caused by F–T cycle is a process of gradual damage accumulation.



(a) *W*=4 mm

(b) *W*=3 mm

(c) *W*=2 mm

Fig. 7 Cyclic frost-heaving pressure curves of sample with 50 mm crack length

By fitting the peak frost heaving pressure of multiple F–T cycles, and the relationship between peak frost heaving pressure of granite samples with different crack widths and number of F–T cycles is obtained, as shown in Fig. 8. It is found that the fitting is best when exponential function is used. The peak frost heaving pressure of granite samples with different crack widths decreases exponentially with the increase of F–T cycles, and the samples with crack width of 2 mm decrease fastest.

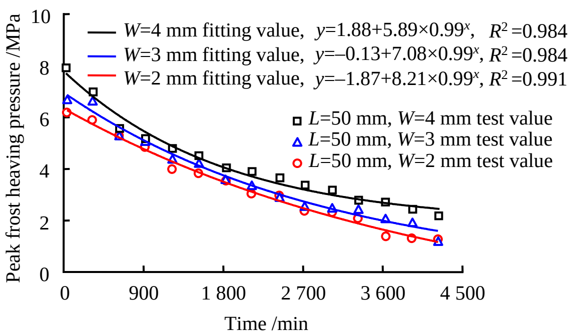


Fig. 8 Fitting curves of peak cyclic frost-heaving pressure

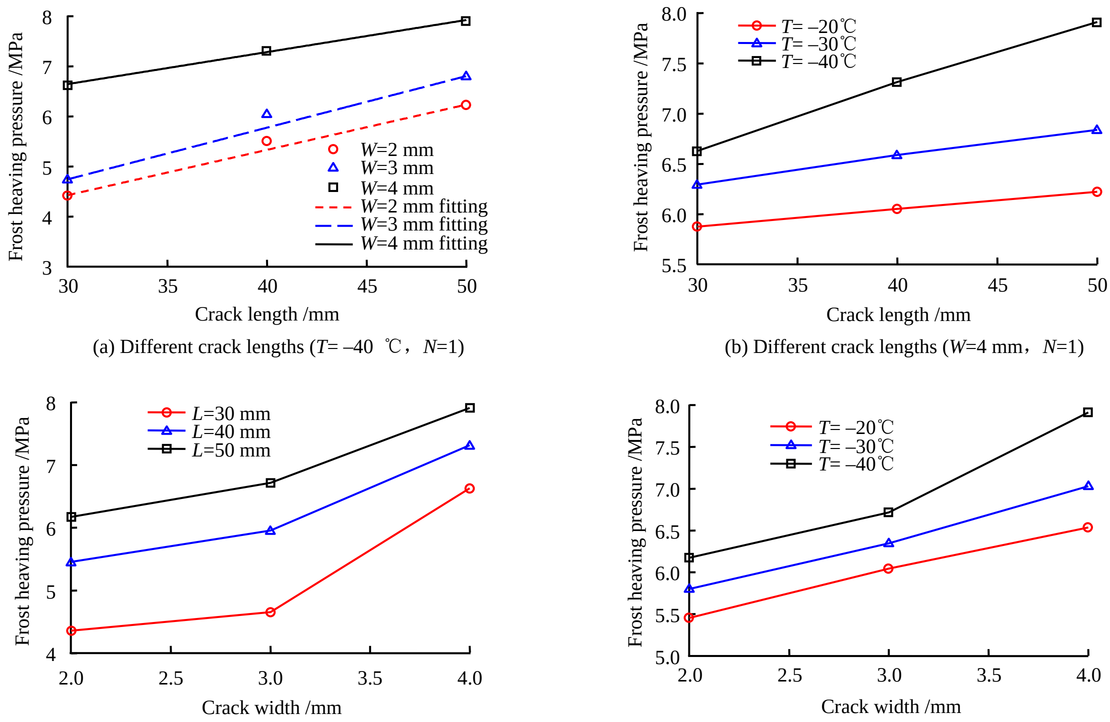
3.2 The influence of crack geometry on frost heaving pressure

When the freezing temperature is –40 ℃ and the number of F–T cycles is 1, the evolution law of peak frost heaving pressure of granites with different crack lengths is shown in Fig. 9 (a).

It can be concluded that for same crack width, as the crack length increases, the peak frost heaving pressure gradually increases, and the peak frost heaving pressure increases linearly with the increase of crack length. When the crack width is 4 mm and the number of F–T cycles is 1, the evolution law of peak frost heaving pressure of granites subjected to different freezing temperatures is depicted in Fig. 9 (b). The peak frost heaving pressure increases linearly with the decrease of freezing temperature. When the freezing temperature is –20 ℃, the peak frost heaving pressure of sample with a crack length of 50 mm increases by 0.47 MPa compared to the sample with a crack length of 30 mm. When the freezing temperature is –40 ℃, the peak frost heaving pressure of sample with crack length of 50 mm increases by 1.74 MPa compared with sample with crack length of 30 mm. Therefore, the lower the freezing temperature, the greater the influence of crack size on peak frost heaving pressure. When the freezing temperature is –40 ℃ and the number of F–T cycles is 1, the evolution law of peak frost heaving pressure of granites with different crack widths is plotted in Fig. 9 (c). The peak frost heaving pressure increases in varying degrees with the increase of crack width. The larger the crack width, the greater the increase of frost heaving pressure caused by F–T cycle. When the crack length is 50 mm and the number of F–T cycles is 1, the evolution law of peak frost heaving pressure of samples subjected to different freezing temperatures is shown in Fig. 9 (d). With the decrease of freezing temperature, the peak frost heaving pressure increases. In addition, the larger the crack width, the more significant the influence of freezing temperature on the peak frost heaving pressure.

3.3 The influence of the number of F–T cycles on the frost heaving pressure

The frost heaving pressure of samples with crack length of 50 mm and freezing temperature of –40 ℃ in the 1st, 3rd, 5th, 10th and 15th F–T cycles is plotted in Fig. 10. As the F–T cycles increases, the peak frost heaving pressure decreases. In the first F–T cycle, the peak frost heaving pressure has a small drop. When the number of F–T cycles reaches 3 times, the peak frost heaving pressure shows significant drop. Moreover, when the number of F–T cycles reaches 10, the peak frost heaving pressure drops to 0, which is mainly because the crack tip is pulled by repeated frost heaving pressure. Undoubtedly, this resulted in a significant release of frost heaving pressure. The smaller the sample crack width, the earlier the frost heaving pressure surge occurs, and the earlier the secondary frost heaving pressure appears in the thawing stage. The smaller the crack width is, the smaller the rock sample water storage. Therefore, the water ice phase change process occurs faster in freezing and thawing stage. The wave velocity test results show that with the increase of F–T cycles, the longitudinal wave velocity gradually decreases, indicating that the F–T cycle has caused gradual damage accumulation of rock sample. Further, the frost heaving pressure will drive the initiation and expansion of micro cracks in rock sample.



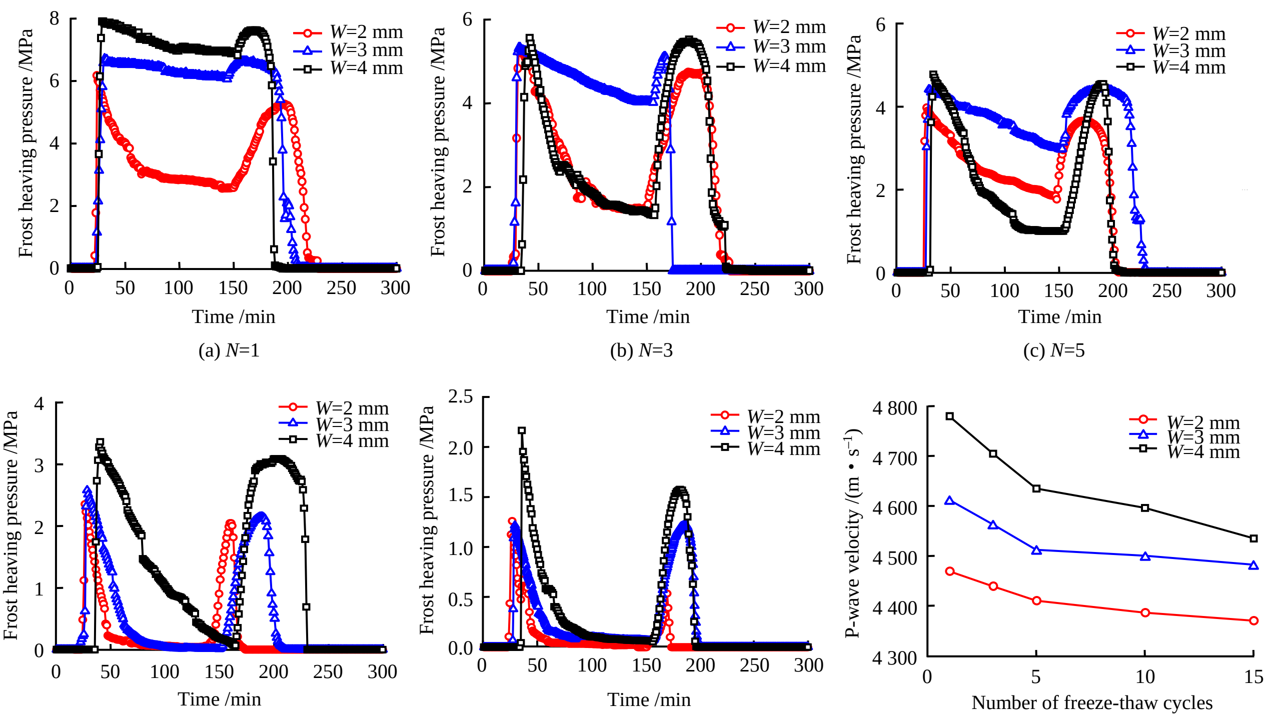
(a) Different crack lengths (*T*= –40 ℃，*N*=1)

(b) Different crack lengths (*W*=4 mm，*N*=1)

(c) Different crack widths (*T*= –40 ℃，*N*=1)

(d) Different crack widths (*L*=50 mm，*N*=1)

Fig. 9 Relationship curves between crack size and peak frost-heaving pressure



(a) *N*=1

(b) *N*=3

(c) *N*=5

(d) *N*=10

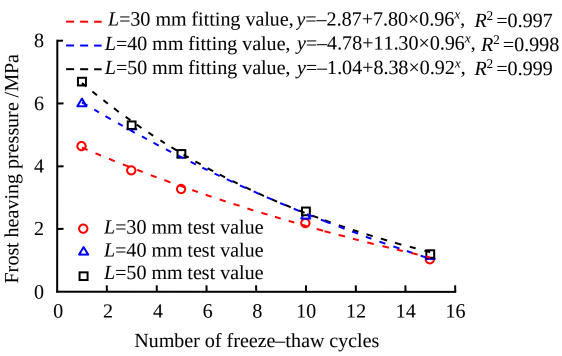
(e) *N*=15

(f) *N*=15

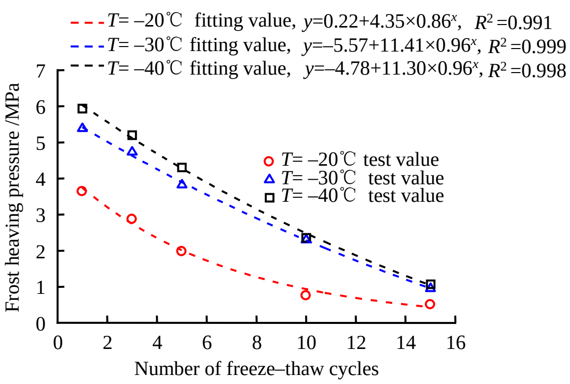
Fig. 10 Frost-heaving pressure and P-wave velocity evolution curves of the 1st , 3rd, 5th, 10th and 15th freeze–thaw cycles with different crack widths (*L*=50 mm，*T*= –40 ℃)

The relationship between peak frost heaving pressure and crack length of samples with 3 mm crack width and –40 ℃ freezing temperature in the 1st, 3rd, 5th, 10th and 15th F–T cycles is shown in Fig. 11 (a). When the number of F–T cycles exceeds 10, the influence of crack size on peak frost heaving pressure becomes smaller. The peak frost heaving pressure of samples with different crack lengths decreases exponentially with increase of F–T cycles. The 15th F–T cycle peak frost heaving pressure of the samples with crack lengths of 30, 40, and 50 mm are 1.66 MPa, 1.48 MPa and 1.42 MPa, respectively. Compared with the 10th F–T cycle, the frost heaving pressure is reduced by 52.6%, 54.2% and 52.7%. It indicated that the reduction degree of rock samples with different crack lengths is basically the same.

Figure 11 (b) plots the relationship between peak frost heaving pressure and freezing temperature of samples with 40mm crack length and 3mm crack width in the 1st, 3rd, 5th, 10th and 15th F–T cycles. The peak frost heaving pressure of samples at different freezing temperatures decreases with increase of F–T cycles exponentially. With the increase of F–T cycles, decreasing rate of peak frost heaving pressure at different freezing temperatures decreases, indicating that the effect of freezing temperature on peak frost heaving pressure decreases with increase of F–T cycles. The peak frost heaving pressure of the 15th F–T cycle at –20, –30 ℃ and –40 ℃ is 0.73 MPa, 1.30 MPa and 1.48 MPa respectively, which decrease by 85.5%, 82.2% and 81.7% compared with the first F–T cycle. In addition, the frost heaving pressure is reduced by 31.1%, 58.4% and 54.2% as compared with the 10th F–T cycle.



(a) The relationship between peak frost heaving pressure and crack length (W=3 mm，T= –40 ℃)

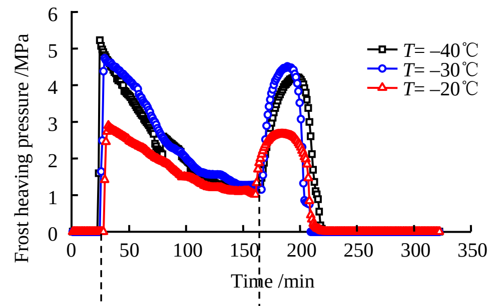


(b) The relationship between peak frost heaving pressure and freezing temperature (L=40 mm，W=3 mm)

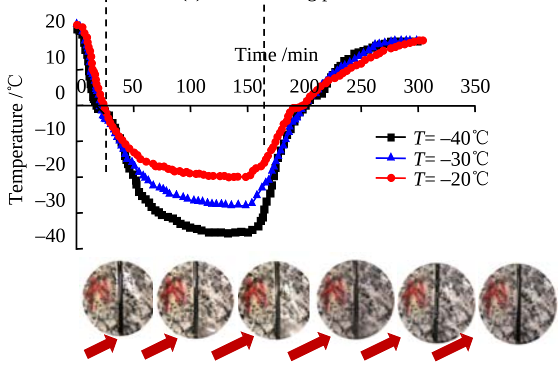
Fig. 11 Relationship between the number of freeze–thaw cycles and peak frost-heaving pressure

3.4 The influence of freezing temperature on frost heaving pressure

The frost heaving pressure and temperature curves of the third F–T cycle of specimen with a crack length of 40 mm and crack width of 3 mm are shown in Fig. 12. The surface temperature of the rock sample decreases from room temperature, and the cooling rate before freezing point is about 1.02 ℃/ min. Then, the rock sample temperature gradually reaches the preset temperature (–20 ℃, –30 ℃ and –40 ℃) and is maintained for 150 min. The rock sample is taken out from the cryopreservation box and melts at room temperature. When the surface temperature of the rock sample reaches 0 ℃, the rising rate of temperature is about 0.53 ℃/ min. And then the temperature gradually returns to room temperature and stands for 300 min.



(a) Frost heaving pressure curves



(b) Freezing temperature curves

Fig. 12 Frost-heaving pressure and freezing temperature curves

When the freezing temperature is –20 ℃, the surface temperature drops to about 0 ℃ in about 23 min, at this time all the cracks are filled with liquid water. The surface temperature of the rock sample is about –8 ℃ when frost heaving pressure appears, and the time for the frost heaving pressure to appear is about 26 min. At this moment, the crack water freezes into ice, and the temperature of rock sample drops to –20 ℃ in about 90 min. During thawing, the frost heaving pressure of rock sample shows a second recovery time of about 151 min, and the surface temperature rise to 0 ℃ in about 200 min. At this time, liquid water appears on the edge of frozen ice in the crack. When the freezing temperature is –30 ℃, the surface temperature decreases to 0 ℃ in about 21 min, at this time all the cracks are filled liquid water. The surface temperature is about –6 ℃ when the frost heaving pressure occurs, and the time of frost heaving pressure occurred is about 24 min. In addition, the rock temperature drops to –20 ℃ in about 100 min. The second rise time of frost heaving pressure is about 155 min. For the rock sample with freezing temperature of –40 ℃, the surface temperature decrease to 0 ℃ in about 17 min. The surface temperature of the rock sample is about –5 ℃ when frost heaving pressure appears, and the time for frost heaving pressure to appear is about 22 min. The rock sample temperature drops to –20 ℃ in about 110 min. The second rise time of frost heaving pressure is about 156 min. Therefore, the lower the freezing temperature is, the earlier the frost heaving pressure of rock samples is generated. In addition, the lower the freezing temperature, the closer the surface temperature to freezing point when the crack water freezes. It indicates that the lower the freezing temperature, the faster the water-ice phase change inside the fractured rock sample.

To further analyze the influence of freezing temperature on peak frost heaving pressure, the frost heaving pressure curves of rock samples with 4 mm crack width and 50 mm crack length during the first F–T cycle are given in Fig. 13. As the freezing temperature decreases, the peak frost heaving pressure of rock sample increases, indicating that the lower the freezing temperature, the greater the damage and deterioration of rock sample caused by F–T treatment. Fig. 13(a) shows that the peak frost heaving pressure of rock samples with 50, 40, and 30 mm crack lengths at –40 ℃ freezing temperature increased by 42.9%, 37.3% and 29.5%, respectively. As shown in Fig. 13 (b), the peak frost heaving pressure of rock samples with crack length of 4, 3 and 2 mm at freezing temperature of –40 ℃ increases by 19.3%, 9.2% and 6.6%, respectively, when compared with –20 ℃.

3.5 Frost heave crack propagation and deterioration mechanism

To further study the water–ice phase change phenomenon in cracks subjected to F–T cycle, image acquisition is carried out on the open crack surface every 20 min. Figure 14 shows the observed crack water–ice evolution process of sample with 50 mm crack length and 3 mm crack width in a single F–T cycle at –40 ℃ freezing temperature. When the rock sample is frozen for 20 min, the liquid water inside crack first freezes at the edge of crack wall at the opening. With further freezing of crack water at the open end, ice jam effect occurs at the opening. It provides a closed space for the generation of frost heaving pressure, which is a necessary condition for the increase of frost heaving pressure. With further freezing, the water in the crack gradually freezes into ice when the rock sample is frozen for 140 min, and

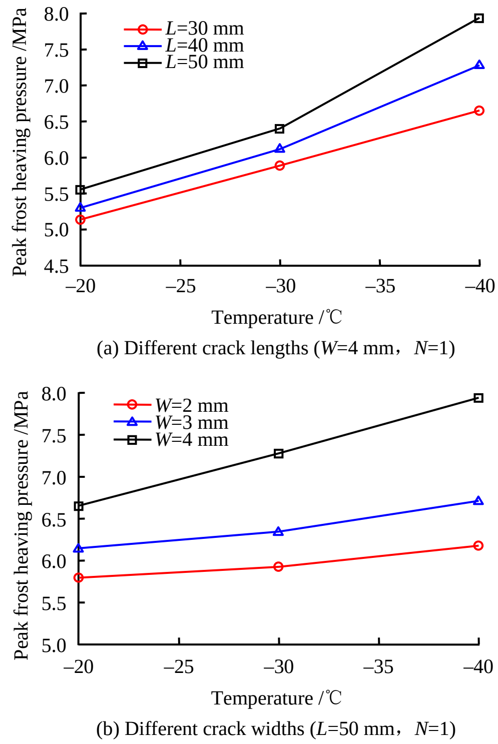


Fig. 13 Relationship between the freezing temperature and peak frost-heaving pressure

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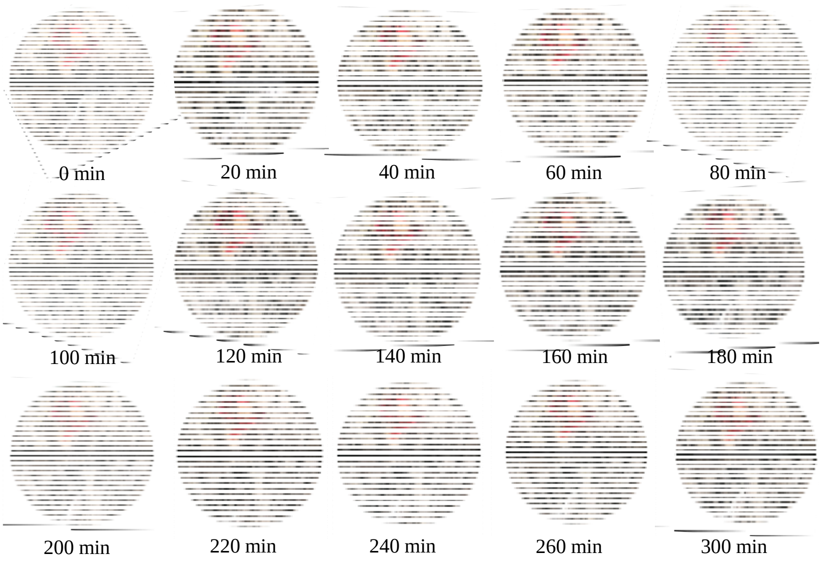

Fig. 14 Image acquisition of water ice phase transition in a freeze thaw cycle

the water–ice phase change is completed. When the sample melts at room temperature, the frozen ice at the opening end of crack becomes loose in 180 min, and the ice near the two sides of crack melts first and liquid water appears. The crack ice gradually melts from the edge of ice core to the center of ice core. After thawing to 220 min, all crack ice melts into liquid water, and the water-ice phase change is completed.

When the frost heaving pressure exceeds the tensile strength of rock matrix during the F–T cycle, crack initiation and propagation occur, resulting in release of frost heaving pressure. At this time, the frost heaving pressure will fall suddenly. Therefore, the frost heaving pressure driven by water–ice phase change and volume expansion of cracks is an important reason for the deterioration of rock properties subjected to F–T cycle. Figure 15 shows the failure of sample with 30 mm crack length and 2 mm crack width during the F–T cycle. It can be clearly seen that there are obvious frost heave cracks at the ends of samples. Therefore, the deterioration effect of F–T cycle on the mechanical properties of water bearing fractured rock mass cannot be ignored.

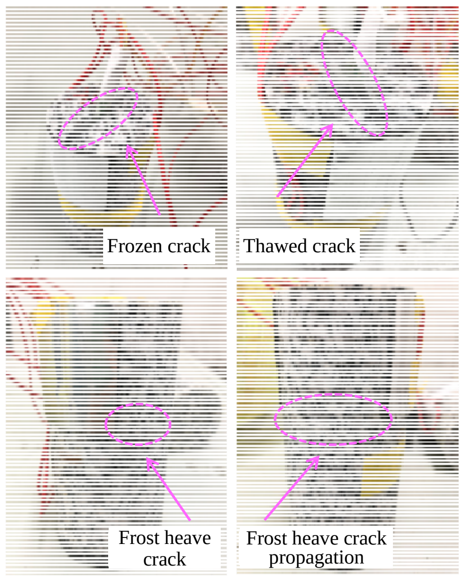

Fig. 15 Crack propagation in rock sample caused by freeze–thaw cycles

This paper analyzes the effects of crack size, freezing temperature and F–T cycle times on the long-term frost heaving pressure of fractured rock, and preliminarily reveals the frost heaving deterioration mechanism of fractured rock. However, the frost heave process of fractured rock involves many influencing factors, and the crack structure is very complicated. Based on the above problems, this paper has conducted a preliminary study on the evolution mechanism of periodic frost heaving pressure of fractured rock as much as possible, to provide reference for further research on the F–T damage mechanism of fractured rock.

4 Conclusion

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(1) Based on the real-time monitoring of laboratory F–T test, this paper explores the evolution characteristics of long-term frost heaving pressure on granites with different crack sizes, and reveals the influence of crack size, freezing temperature and F–T cycles on frost heaving pressure. The frost heaving pressure generated by water–ice phase change and volume expansion of saturated cracks is the fundamental driving force for initiation and expansion of cracks subjected to F–T cycle. It is the leading factor for inducing F–T damage and failure of rock engineering. The evolution curve of single frost heaving pressure can be roughly divided into five stages. The initiation, expansion and dissipation process of frost heaving pressure has a strong corresponding relationship with freezing temperature.

(2) With the increase of F–T cycles, the peak frost heaving pressure decreases exponentially. The crack is gradually pulled apart by the repeated frost heaving pressure, resulting in obvious release of frost heaving pressure. Therefore, with the increase of F-T cycle numbers, the drop of frost heaving pressure after the peak is greater. It also indicates that the degradation effect of F–T cycles on rock is a process of gradual damage accumulation.

(3) With the increase of crack length, the peak frost heaving pressure increases linearly. The smaller the crack width is, the smaller the water storage of rock sample. Therefore, the water–ice phase change process occurs faster in the freezing and thawing stage. Consequently, the smaller the crack width is, the earlier the frost heaving pressure appears, and the earlier the secondary frost heaving pressure appears in the thawing stage.

(4) The temperature of the rock surface is first reduced to zero, and the frost heaving pressure is generated at about –5 ℃. The peak frost heaving pressure increases linearly with the decrease of temperature, and the damage and deterioration of rock sample caused by the F–T cycle is greater. The peak frost heaving pressure decreases exponentially with increase of F–T cycle numbers, and the influence of freezing temperature on peak frost heaving pressure weakens with increase of F–T cycle number. The lower the freezing temperature, the more significant the effect of crack size on peak frost heaving pressure. With the decrease of freezing temperature, the earlier the frost heaving pressure appears, the closer the surface temperature to freezing point when the crack water freezes, indicating that with decrease of freezing temperature, the water-ice change transition in fractured rock samples is faster.

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