Research on Physical and Mechanics Properties of Metamorphic Sandstone Subjected to Freeze-thaw Cycles

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Abstract. The Sichuan-Tibet Railway passed through high-altitude metamorphic rock areas in western Sichuan, where rock freeze-thaw weathered intensely and geological disasters occured frequently, it was of great theoretical significance and engineering value to carry out freeze-thaw cycle tests on typical rocks. The metamorphic sandstone samples collected from the Lancang River Basin were divided into five groups, each group experienced freezing and thawing about 8h (4 h freezing and 4 h thawing) of wide temperature range whose freezing temperature was -40 ℃ and thawing temperature was 50 ℃. During the experiment, loss of quality, change in P-wave velocity of metamorphic sandstone were counted with observing deterioration in the appearance of rock specimens every certain number of cycles, combining with uniaxial compression tests after 22, 42, 65, 85, and 105 times of freeze-thaw cycles respectively. Comparing and analyzing the calculated physical and mechanical parameters, the result shows that with increasing cycles of freezing and thawing, the quality first drops, then reaches a minimum after 40~50 cycles, and oscillates and stabilizes finally. The P-wave velocity of the sample is large after freezing, and is numerically higher than the P-wave velocity after thawing. Overall, the P-wave velocity and quality change trend have good consistency. The uniaxial compressive strength of specimens has no obvious regular pattern. The structural plane has an important influence on the freeze-thaw cycle test results, the research on the mechanism of structural freeze-thaw degradation is an important part of revealing the stability of rock mass in alpine region.

1. Introduction
With the development of railway construction in western China, high-altitude engineering has gradually increased, and freezing and thawing of rock and soil has become one of the major problems which affects engineering construction. On the one hand, the repeated action of freezing and thawing will weather the surface of the rock mass, cause the collapse, spalling and landslide of the rock mass[1], affect the stability of the cold zone slope[2] and also provide the source of the debris flow. On the other hand, as the freeze-thaw cycle aggravates the degree of weathering of the rock mass, the rock and soil become more loose and broken, the water is more likely to reach the deep part of the rock mass, then causes frost heaving damage, tunnels, building foundations and underground pipelines are subject to different degrees of damage[3-5].

Due to the numerous factors affecting the freezing and thawing damage of rocks, there is no unified understanding of the classification of freeze-thaw failure modes[6]. Through laboratory test and field
monitoring, scholars at home and abroad have gradually realized that it is of great theoretical significance and engineering value to understand the influence of rock nature on the freeze-thaw cycle. Lautridou[7], Matsuoka[8] and Nicholson[9] conducted freezing and thawing test on a variety of different rocks, including igneous and sedimentary rocks almost. The results indicated that lithology was one of the decisive factors affecting the mechanism of freeze-thaw degradation. Zhu Liping[10] and Liu Chengyu[11] carried out a comprehensive experimental study of granite, Zhang Huimei[12] and Xu Guang Miao[13] focused on the mechanism of sandstone freezing thawing deterioration, Wu Gang[14] and Fu Helin[15] made a few attempts on freezing and thawing test of marble and slate. Numerous research results show that lithology is the main factor affecting rock freezing thawing degree and deterioration mode.

Although domestic and foreign scholars have done a lot of research on freeze-thaw tests of different rocks, the research objects are mostly concentrated on red sandstone, granite and limestone which are single and sensitive to freeze-thaw, and the research focus is mainly on basic research with little connection with engineering practice. The Luding-Basu section of the Sichuan-Tibet Railway lies in the Hengduan Mountains, spanning the Jinsha, Lancang and Nuijiang rivers. Because of the high relief in the area, vertical zoning of climate is obvious. The temperature difference between day and night is large, a number of exposed metamorphic rocks are subjected to intense freezing and weathering, which is not conducive to the construction of railway projects. Therefore, this paper takes the metamorphic sandstone in the Lancang River Basin as the research object, carries out 105 freeze-thaw cycles at the specified temperature, and determines the physical and mechanical parameters of the sample during the freeze-thaw process. The variation law of parameters is analyzed to reveal the failure characteristics of rock during freeze-thaw cycle. Finally, the test results which have certain theoretical significance and engineering value are generalized and the influencing factors of deterioration of metamorphic sandstone are summarized.

2. Sample Collection and Experimental Technique

2.1 Sample Description and Preparation

The test rock is a representative medium-grain metamorphic quartz sandstone in Lancang River Basin. Owing to the inconvenience of traffic, it is difficult to mobilize large-scale machinery to get deep rock samples, so the shallow rock samples with large size and relatively fresh are usually collected. Because of unloading, there are many macro fractures and joints in rock mass. In order to minimize the influence of macroscopic joint fissures, the samples collecting in the field are processed into cylindrical specimens with a diameter of 25 mm, a height of 50 mm and an apparent integrity without visible joints (Fig.1).

![Fig.1 Specimens preparation of metamorphic sandstone](image)
value was often smaller than that of the frozen sample. With the quality change after freezing, the quality change of sample after thawing was smaller, and the cracks developed intermittently, resulting in a greater change in rock mass after freezing. Compared to the water was preserved in the form of ice after freezing. As the freezing and thawing progressed, the rock samples were weighed after thawing, most of the water in the pores and fractures was lost, and generally greater than that after thawing, and the extent of change was larger. This revealed that when the overall trend was gradually stabilized after the oscillation decreased. The quality after freezing was

| natural density /\text{(g\text{·cm}^{-3})} | P-wave velocity /\text{(m\text{·s}^{-1})} | saturated water absorption /\% | porosity /\% |
|-----------------------------------------------|-----------------------------------------------|---------------------------------|---------------|
| 2.64                                          | 4792                                          | 0.39                            | 1.01           |

2.2 Experimental Procedure
The traditional standard freeze-thaw cycle test has a temperature difference of 40 °C and a minimum temperature of -20 (±2 °C), which often fails to simulate the environmental conditions of high-altitude cold zone projects. The 25 freeze-thaw cycles of the standard test often cause invalid damage to some dense rocks due to too few cycles. Therefore, this paper selects a large temperature difference cycle of -40 (±2 °C) ~ + 50 (± 2 °C) for freeze-thaw test with a total of 105 freeze-thaw cycles simulating the 105 a time in the actual project. The saturated samples were put into the cryogenic tank for anhydrous freezing after the temperature was stabilized, then the samples were taken out after 4 hours and then immersed in a constant temperature water bath at 50 °C for 4 hours. This process was a freeze-thaw cycle.

During the freeze-thaw cycle test, the quality and P-wave velocity of frozen and thawed rock samples were measured at regular intervals, uniaxial compressive tests were carried out on rock specimens after 22, 42, 65, 85 and 105 freeze-thaw cycles respectively, and relevant mechanical parameters were calculated.

3. Experimental Results and Discussions

3.1 Change of Quality
In the traditional freeze-thaw cycle test, the measurement of the quality change of the sample is arranged after the completion of one cycle which often fails to distinguish the quality changes during freezing and thawing. Therefore, in order to show the changes of quality in the process of freezing and thawing more intuitively, the samples after freezing and thawing were weighed and recorded separately every certain number of cycles. Due to the large amount of data, only the quality changes of the samples after 42 and 105 freeze-thaw cycles were listed (Fig.2).

![Fig.2  Quality changes of typical specimens](image)

It could be seen from the above figure that the variation range of the sample quality was small, and the overall trend was gradually stabilized after the oscillation decreased. The quality after freezing was generally greater than that after thawing, and the extent of change was larger. This revealed that when rock samples were weighed after thawing, most of the water in the pores and fractures was lost, and the water was preserved in the form of ice after freezing. As the freezing and thawing progressed, the cracks developed intermittently, resulting in a greater change in rock mass after freezing. Compared with the quality change after freezing, the quality change of sample after thawing was smaller, and the value was often smaller than that of the frozen sample.
It was found that the quality of the sample decreased rapidly after the initial freeze-thaw cycles, which was shown in the first (1) section of the mean change diagram. Subsequently, the quality of the specimens showed oscillatory descent, but the descent rate was far less than that of the initial cycles, which was shown in (2) section of the mean change diagram. When the freeze-thaw cycle lasted for about 40 to 50 times, the quality loss reached the maximum, and then began to oscillate up and down around an interval, and the mass tended to be stable, which was shown in (3) section of the mean change diagram. In addition to the 42 and 105 freeze-thaw cycles, the quality change of other freeze-thaw cycles also showed the same trend (Fig.3). The result indicated that the initial sensitivity of the block to the freeze-thaw cycle was strong, which also reflected the effect of initial damage on the freezing and thawing weathering of rocks. With the continuous freeze-thaw process, the water-ice phase transformation and migration in rock cracks and the discontinuous change of debris shedding made the sample quality show a downward trend of oscillation, which reflected the discontinuous development of cracks in rock from the side. When the test was carried out for a certain number of cycles, the freezing and thawing effect had not penetrated into the interior of the rock sample, and the sample quality tended to be stable.

3.2 Change of Ultrasonic Speed
Ultrasonic speed tests were performed on the samples after freezing and thawing at regular intervals. The following figure showed the variation of P-wave velocity of the rock during 42 and 105 cycles (Fig.4).

It was not difficult to find that since the ultrasonic longitudinal wave propagated far faster in ice than water and air, P-wave velocity of the sample after freezing in the same cycle was generally higher than that after thawing from the above figure. P-wave velocity of the samples after freezing was fast, and the amplitude of variation was much higher than that of the longitudinal wave after thawing. The reason for this result might be that after each freezing, the continuous filling of ice did not reduce P wave velocity of the degraded rock sample, and the strong oscillation reflected the intermittent development of the crack in the sample, each drop in wave speed meant that the ice had not been
completely filled with new cracks, and each increase in wave speed indicated from the side that new cracks were filled with ice.

![Fig. 5. Mean change of ultrasonic P-wave velocity](image)

The average P-wave velocity of the samples after freezing and thawing was plotted in each cycle. It could be found from the diagram that P-wave velocity of No. 119 specimen showed a downward trend as a whole, and the variation process could be divided into (1) and (2) parts. The variation of section (1) showed that the initial cyclic wave velocity decreased rapidly, while the velocity of section (2) continued to decrease after a gentle shock. The P-wave velocity of No. 111 specimen decreased firstly and then oscillated gently. The mean value of P-wave velocity could be divided into three sections. The first section represented the rapid decline of velocity after the initial several cycles, the second section continued to decline sharply after a small rebound, and the third section showed a gentle trend of oscillation (Fig. 5). After 40~50 cycles, the wave velocity reached the minimum, followed by gentle oscillation and no longer declined. From the side, the freeze-thaw cycles had a great deterioration effect on the rock samples in the first half of the test, but due to the nature of the rock itself, it was difficult to continue to aggravate the damage to the rock samples in the second half of the test, and the freeze-thaw weathering had been difficult to penetrate into the deep part of the rock samples and continued to cause substantial damage.

By comparison, the results showed that the variation of sample quality was in good agreement with the variation trend of P-wave velocity, and the variation of quality and P-wave velocity could be used as a reflection index of rock mass weathering by freeze-thaw up to a point.

### 3.3 Change of Uniaxial Compressive Strength

In order to study the effect of freeze-thaw cycles on the mechanical properties of metamorphic sandstone samples, the uniaxial compression tests were carried out on rock samples subjected to different freeze-thaw cycles at room temperature. The test results showed that after 22, 42, 65, 85 and 105 freeze-thaw cycles, the uniaxial compressive strength of the samples were 91 MPa, 156 MPa, 102 MPa, 103 MPa and 158 MPa respectively. The overall change chart was shown below (Fig. 6). There was no significant correlation between the uniaxial compressive strength and the number of freeze-thaw cycles. After 105 freeze-thaw cycles, the uniaxial compressive strength of the sample was the highest value in the test.
In most of freeze-thaw cycle test papers, uniaxial compressive strength of rock was often used as a quantitative index of deterioration failure to get the relevant deterioration model, the result was that the strength decreased with the increase of freeze-thaw cycles. However, in these experimental studies, the experimental purposes were mostly theoretical research, the experimental objects were mostly red sandstone, marble, granite and other rock blocks, and most of these rocks had the characteristics of low strength, high porosity, and weak connection with the actual engineering. The object of this paper was small-sized metamorphic sandstone, which had the characteristics of low porosity, high strength and no apparent cracks. From the changes of physical properties of the samples, it could be seen that the freeze-thaw cycle had a certain damage to the rock, but it could not continue to penetrate into the rock to a certain extent. Therefore, the strength of the sample subjected to the freeze-thaw cycle was not affected when subjected to uniaxial compression. The magnitude of the uniaxial compressive strength value in this paper was mainly determined by the nature of the metamorphic sandstone.

3.4 Discussions

From the lithology point of view, under the condition that the size of the test samples was reduced as much as possible to avoid the existence of macroscopic cracks, the freeze-thaw cycle test under large temperature difference conditions was carried out. The results showed that the physical parameters of the sample had decreased and the mechanical strength was almost unaffected. Although this was different from the results of many papers in which the compressive strength decreased with the increase of freeze-thaw cycles, it was also similar to the results of some scholars. Lautridou[7] had experimentally studied that rocks with a porosity of less than 6% were not susceptible to freeze-thaw damage. By summarizing the results of field investigations, Andre[16] pointed out that lithology had a great influence on freeze-thaw weathering, and it was difficult to explain the freezing and thawing degradation mechanism of all rocks by the same mechanism.

In order to explore the relevant effects of structural planes in the freeze-thaw cycle test, the freeze-thaw cycle test of irregular structured surface specimens was also carried out under the same test conditions. When the test was carried out about 50 times, a specimen was suddenly destroyed into two parts along its internal structural plane without external force, each part was complete with only a small piece of fragment shedding (Fig.7). Different from the freeze-thaw cycle test of the complete cylindrical specimen, even if there was no external force load, the existence of the structural plane still caused the whole rock sample to be destroyed, which could reflect the important role of the structural plane in the freezing and thawing degradation of the rock mass. The test for the freezing and thawing response of the structural surface needed further development.
4. Conclusion

(1) The metamorphic sandstones in the Lancang River Basin had almost no apparent changes before and after freezing and thawing, and the quality changes were small. At the first 5 cycles, the mass decreased rapidly, when the freeze-thaw cycle was carried out to about 40~50 times, the mass loss reached the maximum, then the sample mass began to oscillate around a range and stabilized gradually. The quality of frozen and thawed samples was measured respectively, and it was found that the quality of frozen samples was generally greater than that of thawed samples in the same cycle.

(2) The P-wave velocities of frozen and thawed specimens were measured respectively. It was found that the P-wave velocities of frozen specimens oscillated strongly with the freezing-thawing cycles, and the amplitude of variation was much higher than that of thawed specimens. The discontinuous development of cracks in rock was described from the side. On the whole, P-wave velocity of rock sample decreased rapidly in the first five cycles, when the number of cycles reached 40~50 times, P-wave velocity reached the minimum value, then gradually oscillated and tended to be stable.

(3) The variation of sample quality and P-wave velocity was in good agreement. The variation trend of them was an objective reflection of freeze-thaw damage in rock, and could be used as an indicator of rock mass weathering to a certain extent.

(4) In this paper, small-sized metamorphic sandstone was tested, which had the characteristics of low porosity, high strength and no apparent cracks. Therefore, when the specimen was subjected to uniaxial compression, there was no significant relationship between compressive strength and freeze-thaw times.

(5) The freeze-thaw failure phenomenon of irregular rock mass with structural plane reflected the important role of the structural plane in the freezing and thawing degradation of rock mass. The research results in this paper are preliminary. In the future work, the research on the mechanism of freezing and thawing of structural surface is an important part of revealing the stability of rock mass in alpine region.

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