Physical and mechanical characteristics of saturated tuff under the freeze–thaw cycle

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Abstract. The freeze–thaw cycle of rocks is a research hotspot in the field of geotechnical engineering, and it significantly affects the eastern part of the Zhejiang Province in China. In this study, we test 40 occurrences of freeze–thaw cycles on tuff from the Ningbo area and investigate the variation of the physical and mechanical properties. The results show that only a small amount of debris falls off the saturated tuff samples during the freeze–thaw cycle. The overall quality of the rock sample gradually decreases with the increase in the number of freeze–thaw cycles. However, the average loss rate of the quality is extremely low, accounting for only 0.07% of the rock sample quality. The wave velocity of the rock sample gradually decreases, and the extent of reduction decreases when the number of cycles increases. In the uniaxial compression test, a failure surface appears for the rock samples with low freeze–thaw cycles. The complete failure surface of the samples gradually disappears. Moreover, the compressive strength of the samples progressively decreases with the increase of the number of freeze–thaw cycles.

1. Introduction
With the long-term erosion of water and temperature changes, the rock mass exerts different effects on strength and stability. Cold and severely cold regions comprise 75% of China [1]; hence, the effects of the freeze–thaw degradation of rock masses are widely distributed therein. In many geotechnical projects, various rock mass properties have been affected by different degrees of deterioration that arise from long-term freeze–thaw cycles, which has resulted in numerous disasters with substantial losses.

A freeze–thaw cycle test on rock samples can simulate the influence of the freeze–thaw cycles on the mechanical properties of rock masses to obtain relevant laws and provide a basis for future research. Numerous research results on the influence of freeze–thaw cycles on the mechanical properties of rock masses are available, and many important research outcomes have been achieved. Some scholars have conducted in-depth studies on the changing laws of the physical and mechanical properties of rocks under different freeze–thaw cycles. Park conducted experiments on granite and sandstone and found that the thermal conductivity of rock increases with the decreasing temperature, while the specific heat capacity and thermal expansion coefficient decrease with the decreasing temperature [2]. Momeni et al. conducted 300 freeze–thaw cycle tests on three different types of Alvand granite rocks in Iran to examine the changing laws of the physical and mechanical properties of three rock types [3]. Ghobadi et al. applied a freeze–thaw cycle test on sandstone in western Iran, analyzed the physical and mechanical characteristics of that sample, and used a decay function model to statistically analyze its disintegration rate [4]. Meanwhile, Zhong et al. conducted a freeze–thaw cycle test of a soil–rock
mixture and a large-scale indoor triaxial test to investigate the change law of the mixture’s damage properties. They used PFC3D to simulate the mesoscopic change law of the mixture [5]. Kodama et al. studied the influence of water content, temperature, and loading rate on the strength of two types of rock and analyzed the damage law [6]. Fener et al. selected fresh andesite endorsed as the research object and performed a freeze–thaw cycle test to investigate the influence of the number of freeze–thaw cycles on the basic physical and mechanical properties of andesite [7]. Khanlari et al. performed different dry–wet, freeze–thaw, and temperature cycles on Iranian sandstone and studied the effects of the cycles under various conditions on the physical and mechanical properties of sandstone. They also identified that the freeze–thaw cycles had the most obvious effects on sandstone among the three conditions [8]. Ni pretreated granite with different pH solutions, performed a freeze–thaw cycle test for 100 times on the processed granite, and analyzed its uniaxial compressive strength, axial strain, and other physical and mechanical properties [9]. Tan et al. performed a freeze–thaw cycle test on granite and obtained the variation law of its modulus, cohesion, and internal friction angle from its stress and strain results [10]. Moreover, Liu and Yin et al. analyzed the deteriorating law of the tensile strength of granite under different freeze–thaw cycles using the Brazilian disk test [11,12]. Some scholars also established corresponding theoretical models for freeze–thaw damage. Duca et al. studied the influence of permafrost conditions on various gneiss properties through laboratory simulations and obtained thermodynamic model simulation test results [13]. Faith et al. performed a freeze–thaw cycle test on Turkish limestone samples and established a uniaxial compression strength statistical model for predicting the loss rate of the uniaxial compression strength on the basis of statistical principles [14]. Ghobadi et al. predicted the long-term durability of tuff to freeze–thaw cycles according to the attenuation function [15]. Qu et al. conducted an acid-environment freeze–thaw cycle test on yellow sandstone and established an acid-environment freeze–thaw test damage model according to statistical rock damage evolution equations and the constitutive model strength theory [16]. Huang and Esami et al. studied freeze–thaw cycling rock damage characteristics under different stress fields and established corresponding damage models [17,18]. Some scholars also used instruments to analyze the changes in the microscopic size of rocks under freeze–thaw cycles. Luo et al. used X-ray diffraction and other detection methods to analyze the mineral composition of different types of databases and the changes in their destruction characteristics under freeze–thaw cycles [19]. Li et al. studied the evolution and the damage mechanism of the sandstone microstructure under 180 freeze–thaw cycle tests using the nuclear magnetic resonance (NMR) method [20]. Yang and Gao placed quartzite and red sandstone in different HP solutions and performed freeze–thaw cycle tests using an electron microscope and the NMR technology to analyze the chemical structure and freeze–thaw cycle effect of the quartz rock microstructure changes [21,22]. In summary, extensive research on the various physical and mechanical properties of sandstone, granite, and other rocks under freeze–thaw cycles exists, but relatively little investigation has been conducted on the physical and mechanical properties of tuff. With the gradual increase in the temperature difference, the southern area of China is being gradually affected by the freeze–thaw cycle. However, many scholars still mainly focused on permafrost regions and did not perform detailed studies on rock slopes. Therefore, the present study investigates the influence of freeze–thaw cycles on the rock slopes in Zhejiang, China.

We will identify herein the changes in the physical properties of tuff, including compressive strength and wave velocity, through the freeze–thaw cycle test, mass, ultrasonic measurement, and uniaxial compression test to reveal the degradation mechanism of the various physical and mechanical properties of tuff under the action of a freeze–thaw cycle. This work provides reference and theoretical basis for investigating the change in various properties under the freeze–thaw cycle of this kind of rock slope.

2. Sample preparation and experiment process

2.1. Sample preparation and screening
For the test, we used original tuff from the Ningbo area. The surface of the original sample had no cracks and appeared gray in the natural state. As shown in Figure 1 and according to the national rock
test specifications, the cylinder rock samples measured 100 mm × 50 mm and were presented as is. The flatness, side length, diameter, and verticality of the sample all satisfied test requirement specifications.

After completing the sample preparation, we first removed the samples with large surface gaps. A non-metallic detector was then used to perform the wave velocity test. During testing, the acoustic wave-transmitting probe was placed on the lower side of the sample, while the acoustic wave-receiving probe was placed on the upper side of the sample. The connection between the sample and the probe was coupled with petroleum jelly. Accordingly, weight was applied on the acoustic wave-receiving probe to render it close to the rock surface. After the test completion, the rock samples with the same wave velocity accounted for five groups with three samples in each group. We measured its physical characteristics and present the results in Table 1.

![Figure 1. Sample preparation: (a) initial rock samples; (b) cutting and grinding machine; (c) wave velocity sampling; and (d) standard sample.](image)

| Average dry mass (g) | Average saturated water quality (g) | Average natural density (kg·m⁻³) | Average natural moisture content (%) |
|---------------------|-----------------------------------|---------------------------------|-------------------------------------|
| 596.63              | 597.23                            | 3041                            | 0.05                                |

2.2. Introduction to the test instruments

In the test, we used the DW-45W208 ultra-low-temperature test box that utilizes a stainless steel liner and an imported refrigeration unit with strong anti-corrosion ability, stable performance, high reliability, good insulation performance, and fast cooling speed (i.e., the internal temperature can be reduced from 30 °C to −40 °C in 2 h cooling) (Figure 2). The ultrasonic RS-ST01C non-metallic
ultrasonic detector used in the rock sample classification had high precision and strong anti-dryness. The temperature range of the electric heating constant temperature box used for the melting process was 20 °C to 300 °C. The internal temperature stability was high. The limit value of the universal test machine for the load test of the mechanical properties of the rock sample was 600 KN, a value that meets the test requirements. The accuracy of the measurement feedback value was high.

Figure 2. Test instrument diagram: (a) ultra-low-temperature test chamber; (b) non-metal tester; (c) electric thermostat; and (d) universal testing machine.

2.3. Test method
We adopted the following experimental methods to simulate the freeze–thaw cycle of rocks under natural conditions:
(1) The samples used in this test were divided into five groups with three samples in each group. The groups consisted of saturated water, freeze–thaw cycles for five, 20, and 40 times, and the standby groups. Three test blocks simultaneously participated in the freeze–thaw cycle. The spare group of samples was employed for testing when a problem occurred with the sample. All marked samples were placed into the drying oven. The temperature was controlled at 107 °C ± 1 °C after drying for 24 h to constant weight. The quality was then recorded. The accuracy requirement was 0.01 g.
(2) The sample was saturated with natural saturated water for 48 h after the dry mass measurement completion. The surface moisture was then removed, and the sample was dried to weigh and calculate the natural water absorption rate.
(3) The specimens were removed in their natural state. Strain gauges were attached for the uniaxial compression test. The universal testing machine was loaded at 0.5 MPa/s rate until the specimens were destroyed. The failure mode, uniaxial compressive strength, and elastic modulus were recorded. The values were expressed using three significant digits.
(4) The remaining three groups of saturated rock samples were covered with a plastic wrap to minimize the impact of water evaporation [23,24]. They were then placed in a low-temperature test.
box (−20 °C ± 1 °C) for 6 h and deposited in a stable temperature chamber (20 °C ± 1 °C) for 2 h. The cycle length should meet the conditions of complete freeze–thaw cycles after testing. Thus, the cycle period lasted for 8 h. After reaching the required number of cycles, the corresponding rock samples were removed and weighed. Each freeze–thaw cycle must be recorded in detail to determine whether any blocks or cracks occurred in each cycle. The strain gauges were attached, and a uniaxial compression test was performed once the number of cycles is completed. The universal testing machine was loaded at 0.5 MPa/s rate until the sample was destroyed. The uniaxial compressive strength and the elastic modulus of the sample were then calculated.

3. Analysis of the physical properties of tuff

3.1. Apparent changes of the sample

Figure 3 shows that none of the samples fell off after 40 freeze–thaw cycles. However, a small amount of debris was found on the edge of the sample. This phenomenon may have been caused by the tuff being relatively dense and the sample being affected by the freeze–thaw cycle. Subsequently, the crack penetration inside the corners became more difficult than the internal crack penetration. Therefore, a small amount of peeling occurred at the edges, and the overall appearance of the sample did not change much after 40 freeze–thaw cycles.

Figure 3. Apparent change of the sample after a freeze–thaw cycle.

3.2. Change law of the sample quality

Table 2 and Figures 3 and 4 indicate that the sample quality gradually decreased as the number of cycles increased. Furthermore, the decreased amplitude increased with the number of cycles, thereby showing a trend of initially increasing and then decreasing. However, the overall quality changes are minimal. By contrast, the pore water gradually underwent phase change and produced a frost heave force on the pore wall as the temperature decreased. When the frost heave force was greater than the connection force of the sample particles, the former inflicted an irreversible frost heaving damage on the pore wall, thereby causing the particles in the sample to fall off and the cracks to possibly expand. Tuff is a relatively dense rock with few pores on the outer surface; thus, the frost heave force generated on the outer surface was slight, and the final measurement quality data changes were not obvious. The following formula was used to calculate the average rock mass loss rate:

\[ S = \frac{m_1 - m_2}{m_1} \times 100\%, \]

where, \( S \) is the rock mass freeze–thaw loss rate; \( m_1 \) is the initial rock sample mass; and \( m_2 \) is the end test mass.

According to the formula, no loss of sample quality occurred at five freeze–thaw cycles. However, the damage rate gradually increased from 0% mass loss for five cycles to 0.07% mass loss for 40 cycles with the increase of the number of cycles. The effect of the initial freeze–thaw cycle on the sample was not obvious because the sample was relatively dense at the beginning of the test. The sample
produced fatigue damage when the number of cycles was increased, thereby resulting in the gradual increases of the internal pores and the mass loss. The mass loss rate of 40 freeze–thaw cycles is usually only 0.07% of the rock sample quality. These data reflected that the tuff was relatively dense.

Table 2. Variations of the average tuff mass under freeze–thaw cycles.

| Number of freeze–thaw cycles | Average mass of the saturated rock sample after a freeze–thaw cycle test (g) | Mass difference (g) |
|-----------------------------|----------------------------------------------------------------------------|---------------------|
| 5                           | 589.65                                                                     | 0                   |
| 10                          | 589.53                                                                     | 0.12                |
| 15                          | 589.41                                                                     | 0.24                |
| 20                          | 589.37                                                                     | 0.28                |
| 25                          | 589.26                                                                     | 0.39                |
| 30                          | 589.24                                                                     | 0.41                |
| 35                          | 589.21                                                                     | 0.44                |
| 40                          | 589.20                                                                     | 0.45                |

Figure 4. Variations of the tuff quality as the number of freeze–thaw cycles increases.

3.3. Variation rule of the sample wave velocity

The test used pre-test and post-test measurement data methods to conduct an ultrasonic-speed measurement and prevent the internal moisture loss, which would affect the test results. All experimental data were divided into nine groups (i.e., F1, F2, F3...F9) according to the number of freeze–thaw cycles (i.e., 0, 5, 10... 40) (Table 3).

Table 3. Tuff wave velocities under different freeze–thaw cycle groups.

| Freeze–thaw cycle group | Initial saturated wave velocity (km/s) | Wave speed after the test (km/s) |
|-------------------------|----------------------------------------|---------------------------------|
| F1                      | 3.17                                   |                                 |
| F2                      | 3.17                                   | 3.16                            |
| F3                      | 3.17                                   | 3.15                            |
| F4                      | 3.17                                   | 3.13                            |
| F5                      | 3.17                                   | 3.125                           |
Table 3 shows that the wave velocity of the sample gradually decreased with the increase of the number of freeze–thaw cycles, and the maximum change within the 40 freeze–thaw cycles was 0.18 km/s. This result can be attributed to the pore wall of the rock being constantly subjected to the freeze–expansion force because of the freeze–thaw cycle. The internal particle connections of the rock sample began to be destroyed when the number of cycles increased to a certain degree. The pores also gradually expanded and penetrated, thereby resulting in a gradual decrease in the rock sample density and the progressive decrease in the wave velocity.

![Wave velocity change](image)

**Figure 5.** Variation rule of the sample wave velocities under different numbers of freeze–thaw cycles at increments of five cycles.

Figure 5 indicates that the difference in the change rate of the sample wave velocity before and after the five-cycle increments showed a trend of increasing first and then decreasing with the increase of the number of cycles, except for the 20 freeze–thaw cycle points. Before the 20 freeze–thaw cycles, the pore expansion was relative to that after the 20 freeze–thaw cycles. The former was more intense, but the expansion gradually decreased as the number of cycles increased. The decrease rate in the wave velocity was reduced as the number of freeze–thaw cycles increased (Table 3 and Figure 5). The change rate of the wave velocity before and after the sample test with the 40 freeze–thaw cycles was also low. Although the internal density of the rock began to change, the degree of change was not extensive. Therefore, the degree of crack propagation and the drop of internal particles in the sample gradually increased with the number of cycles, albeit the change being generally not very apparent.

### 3.4. Law of particle size after rock failure

Figures 6 and 7 depict the fragments collected after the uniaxial test of tuff. A certain failure surface occurred in the uniaxial compression failure of the rock sample when no freeze–thaw cycle transpired or during the early stage of the freeze–thaw cycle (Figure 6). However, with the increase of the number of freeze–thaw cycles, the sample failure site was no longer destroyed according to several failure surfaces. Nevertheless, the rock sample was more fully destroyed as the number of freeze–thaw cycles increased. The large-sized fragments gradually decreased after the rock sample was destroyed. The main failure surface was also inclined from the initial surface and gradually turned to the vertical surface. No obvious damage surface occurred (Figure 7). This phenomenon suggests that the internal cracks in the rock gradually expand as the number of freeze–thaw cycles increases, thereby resulting in a gradual increase in the area, where the rock sample is damaged under the uniaxial compression test. Finally, numerous small rock sample fragments appeared after the rock sample was destroyed.
Combining the apparent change of the sample, quality change, wave speed change, and particle size change rule after the destruction revealed that with the freeze–thaw cycle for the saturated tuff, the internal cracks in the rock sample gradually increased as the number of cycles increased. However, the drop particles cannot be discharged; thus, insignificant changes in the mass transpired, albeit the wave speed being gradually decreased.

**Figure 6.** Rock sample after uniaxial compression failure: (a) zero freeze–thaw cycle; (b) five freeze–thaw cycles; (c) 20 freeze–thaw cycles; and (d) 40 freeze–thaw cycles.

**Figure 7.** Failure surface of the rock sample under uniaxial compression: (a) zero freeze–thaw cycle and (b) five freeze–thaw cycles.

4. Analysis of mechanical properties of tuff
Uniaxial compression tests were conducted on the rock samples with different freeze–thaw cycles according to the test requirements to study the change of the mechanical properties of tuff under different freeze–thaw cycles. Representative sample data graphs were selected according to the experimental results. The graphs were summarized into stress curves under different freeze–thaw cycles.

![Stress curves under different freeze–thaw cycles](image)

**Figure 8.** Stress curves under different freeze–thaw cycles.

According to the results of the laboratory uniaxial compressive strength test of tuff, the stress value was calculated; the change of the tuff stress was analyzed under different cycle times; and a graph was drafted. The test result analysis indicated that the compressive strength of the rock continued to decrease as the number of freeze–thaw cycles reached 40 (Figure 8). During the first 40 freeze–thaw cycles, the fissure water in the internal fissures of the rock experienced a 9% volume expansion during the freezing process. This expansion produced an irreversible frost heave force on the pore wall. The frost heave force was greater than the rock strength; hence, the rock pores expanded, resulting in a decrease in the compressive strength [25]. However, during the continuous freeze–thaw cycle, the inside of the rock was also compacted, resulting in the rock strength increase. The experimental results suggest that the degree of compaction was less than the degree of crack propagation; thus, the rock strength continued to decrease within 40 freeze–thaw cycles. However, the intensity reduction rate gradually decreased with the increase of the number of cycles. The strength value of the freeze–thaw cycle 5 times reduced from the most open was 57 MPa, and the final freeze–thaw cycle decreased 20 times to 26.9 MPa. Fitting the compressive strength map of tuff under the freeze–thaw cycle (Figure 9), the change law of the uniaxial compressive strength of the freeze–thaw cycle satisfies the following formula:

$$\sigma = 211 \times (1 + n)^{-0.2},$$

(2)

where, $\sigma$ is stress/MPa, and $n$ is the number of freeze–thaw cycles.
Figure 9. Variations of the uniaxial compressive strength of tuff under different freeze–thaw cycles.

The stress–strain curve of the rock sample was drawn under different freeze–thaw cycles. Figure 10 depicts that the internal crack expansion in the rock sample gradually increased as the number of freeze–thaw cycles increased, thereby resulting in a gradual decrease in the stress and strain. Before and after the freeze–thaw cycle test, the shape of the stress–strain curve of the saturated tuff had similar characteristics as a whole. The stages can be divided into the compaction, deformation, and failure stages. In the compaction stage, the rock sample has a small deformation because of its high strength. The deformation stage of the rock sample will gradually become an elastic deformation stage until the failure stage as the number of cycles increases. In the failure stage, the steep curve shows that the rock sample is suddenly broken. In addition, the longitudinal deformation of the rock sample is small when it is broken. This phenomenon indicates that the texture of the rock sample after the freeze–thaw cycle is brittle, and its bearing capacity becomes poor as the number of cycles increases.

Figure 10. Stress–strain curves of the rock samples under different freeze–thaw cycles

The freeze–thaw coefficient formula is given as follows by the rock test code for water conservancy and hydropower engineering [26]:

\[ K_f = \frac{\bar{R}_f}{\bar{R}_S} \]  

(3)

where, \( K_f \) is the freeze–thaw coefficient of a rock; \( \bar{R}_f \) (MPa) is the average value of the saturated uniaxial compressive strength after the freezing and thawing test; and \( \bar{R}_S \) (MPa) is the average value of the saturated uniaxial compressive strength before the freezing and thawing test.

Using Eq. (3) revealed the change law of the freeze–thaw coefficient of the saturated tuff with the increase in the number of freeze–thaw cycles. The freeze–thaw coefficient gradually decreased as the number of cycles increased; however, the degree of decrease progressively reduced (Table 4).

Table 4. Freeze–thaw coefficients under different cycle times.

| Lithology | Natural state | Five freeze–thaw cycles | 20 freeze–thaw cycles | 40 freeze–thaw cycles |
|-----------|---------------|-------------------------|----------------------|----------------------|
| Tuff      | 1.0           | 0.72                    | 0.55                 | 0.42                 |

5. Conclusion

This study performed a freeze–thaw cycle test on tuff taken from Ningbo, Zhejiang Province and investigated the changes of its physical and mechanical properties. The following conclusions are drawn herein:

(1) A small amount of debris fell off the corners of the tuff samples as the number of freeze–thaw cycles increased; however, no considerable shedding and freeze cracking occurred during the freeze–
thaw cycle. The law of the rock sample quality change indicated that with the increase of the freeze–thaw cycles, the mass loss rate gradually increased; the overall quality change was slight; and the loss part accounted for only 0.07% of the rock sample quality.

(2) The wave velocity of the tuff sample gradually decreased with the increase of the number of freeze–thaw cycles. For 10 freeze–thaw cycles, the wave velocity of the rock sample did not substantially change. It only decreased by 0.02 km/s. The wave velocity difference gradually rose as the number of freeze–thaw cycles increased; however, the increase rate progressively lowered.

(3) With the increase in the number of freeze–thaw cycles, the fragments gradually changed from large to small after the uniaxial compression failure of the sample. The failure surface also changed from initial failure according to the failure surface to the final non-obvious failure surface. After 40 freeze–thaw cycles, the compressive strength of the rock sample gradually decreased, but the decrease was slowly reduced. The freeze–thaw coefficient of tuff gradually decreased with the increase in the number of cycles. Moreover, the freeze–thaw coefficient was progressively lowered to 0.42 after 40 freeze–thaw cycles.

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