An experimental study on characteristics of impact compression of freeze–thawed granite samples under four different states considering moisture content and temperature difference

Bo Ke1,2 · Chunyang Zhang1,3 · Chuanju Liu3 · Linmin Ding4,5 · Yun Zheng2 · Ning Li1 · Yixian Wang6 · Hang Lin7

Received: 8 April 2021 / Accepted: 6 September 2021 / Published online: 21 September 2021
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2021

Abstract
The mechanics of rock masses in cold regions have attracted the attention of researchers from all over the world, and the concern here is that the mechanical properties of rock masses are inevitably weakened under freeze–thaw cycles. In this paper, first, granite samples were subjected to different freeze–thaw cycles, and then treated in four different states, such as saturated and frozen states, saturated and normal temperature states, dry and frozen states, as well as dry and normal temperature states. The impact compression test was carried out using the Split Hopkinson Pressure Bar (SHPB) device. Results show that the impact strength of granite samples deteriorates with the increase of freeze–thaw cycles in the same state; for samples in different states, although the number of freeze–thaw cycles is equal, the degree of deterioration of the impact strength is different. For freeze–thawed granite samples in the same state, the dynamic elastic modulus decreases with the increase of freeze–thaw cycles, and its degree of decrease is different for different states. Under the same freeze–thaw cycles, the deterioration of mechanical properties of granite samples is different in four different weather states; for example, the dynamic elastic modulus from large to small is generally as follows: saturated and frozen states, saturated and normal temperature states, dry and frozen states, as well as dry and normal temperature states. Finally, the freeze–thaw influence factor is proposed to describe the damage of granite samples. All in all, it can be concluded that water and low temperature strengthen the influence of freeze–thaw cycles on the dynamic mechanical properties of granite.

Keywords Granite samples · Freeze–thaw cycles · Impact compression test · Impact strength · Dynamic elastic modulus · Freeze–thaw influence factor

Introduction
Rockmass stability, on one hand, depends on the geological conditions and mechanical properties (Cao et al. 2020c; Fan et al. 2021a, b; Zhao et al. 2020b; Zheng et al. 2021; Li et al. 2021a, b; Lin et al. 2020a; Zhang et al. 2019, 2021), and, on the other hand, is affected by variable external conditions, such as water (Zhang et al. 2020a), temperature (Deprez et al. 2020a), external load (Lin et al. 2020c), etc. As an example, freeze–thaw (FT) weathering deteriorates the mechanical properties of rock masses in areas where the temperature periodically fluctuates around the freezing point (Deprez et al. 2020a, b). Kellerer-Pirklbauer (2017) considered that freeze–thaw cycles and effective freeze–thaw cycles for frost shattering are mainly affecting near-surface rock masses (Gorbatevich 2003; Ziegler et al. 2014; Freire-Lista and Fort 2017); Langman et al. (2017) found that the fluctuation of the freeze–thaw cycle caused the greatest...
sulfide weathering near the surface. However, Xu et al. (2019) pointed out that the instability of rock slope in the freeze–thaw mountains has abrupt and uncertain characteristics, and its prediction accuracy often is very low. Therefore, considering the complexity of freeze–thaw process of rock masses in cold regions, the achievements are mainly based on indoor experiments rather than field experiments.

It is well known that the mechanical properties of rock masses are inevitably affected after repeated freeze–thaw cycles, and many achievements have verified this statement. Ke et al. (2020) declared that the dynamic Young’s modulus and peak stress first increase and then decrease with increasing axial pre-compression stress at the same number of freeze–thaw cycles; Lu et al. (2021) stated that the strength variation law established by the single discontinuity theory is in good agreement with the uniaxial and triaxial test results; Sinclair et al. (2015) reported that the northern waste rock pile drainage geochemistry is strongly influenced by freeze–thaw cycling; Shen et al. (2020) concluded that the F–T cycles have a significant effect on the bonding performance of concrete–granite interface caused by the deterioration effects of cementation; Hashemi et al. (2018) verified that the ultrasonic parameters of maximum amplitude, spatial attenuation, and compressional wave velocity were changed after freeze–thaw tests; Cao et al. (2020a) found that the fracture paths of the SCB specimens subjected to F–T treatments are more tortuous than those in specimens without F–T treatment.

Generally speaking, the mechanical properties of rocks are gradually weakened with the increase of freeze–thaw cycles. For example, the weakening of physical properties of rocks caused by multiple freeze–thaw cycles can be reflected in the changes of porosity, wave velocity, strength and growth of microcracks, etc. (Freire-Lista et al. 2015; Shen et al. 2016; Bost and Pouya 2017; Wang et al. 2019a); The high porosity and weakening of bonds between the carbonate grains is reflected in the very low tensile strength values obtained after ten freeze–thaw cycles (Pápay and Török, 2015); The freeze–thaw damage grows quickly with increasing saturation and freeze–thaw cycles after exceeding the critical saturation (Liu et al. 2020c); compared to fresh specimens, red sandstone after 10 F–T cycles performs poorly in both the static compression and SHPB impact tests (Wang et al. 2016); the long-term strength of red sandstone presents apparent decreasing trends with an increase in the F–T temperature range (Wang et al. 2021a); the Uniaxial Compression Strength of rocks decreases significantly with the increase of moisture content during F–T cycles (Li et al. 2020); the freeze–thaw cycle progression led to decreases in point load strength, Schmidt hardness, and weight and an increase in porosity of the specimens (Sarici and Ozdemir 2018); the mechanical parameters of sandstone had a significant damage deteriorating trend under freeze–thaw cycles (Han et al. 2020); the tangent modulus, total input strain energy, releasable elastic strain energy, and dissipated energy of samples decrease with the increase of F–T cycles (Deng et al. 2019); F–T treatment decreases both fatigue strength and strain energy of marble (Wang et al. 2021b); Lin et al. (2020b) considered that the deterioration of jointed rock masses is mainly due to the frost heaving pressure. All in all, the weakening law of mechanical properties of rock masses in cold regions is helpful to analyze the damage mechanism and prevent disasters.

At present, the study of rock mechanics in cold regions has gradually become one of the hot topics, and the application of new technologies and means promotes its development, such as Nuclear Magnetic Resonance (NMR) technology (Ding et al. 2020; Zhou et al. 2015; Liu et al. 2020a, b, 2021; Jia et al. 2020; Pan et al. 2020; Zhang et al. 2020d), Ultrasonic Detections (Ding et al. 2020; Wang et al. 2017, 2019b; Çelik 2017; Ivankina et al. 2020), Digital Image Correlation (DIC) (Mardoukhi et al. 2021), Neutron Diffraction Measurements (Ivankina et al. 2020), Scanning Electron Microscope (SEM) (Wang et al. 2017, 2019b; Çelik 2020; Chang et al. 2020; Abdolghanizadeh et al. 2020; Fang et al. 2018; Zhou et al. 2018, 2019; Yang et al. 2021b; Zhao et al. 2019), Computed Tomography (CT) technique (Wang et al. 2020b), Optical Microscope (Çelik 2020; Mousavi et al. 2020), X-ray Computed Micro-tomography (Deprez et al. 2020b), X-ray diffraction (XRD) (Zhao et al. 2019; Mousavi et al. 2020), Acoustic Emission (Wang et al. 2020b; Xiao et al. 2020), and Infrared thermography (Yang et al. 2021a). These new techniques and their combined applications help to discover new features in experiments and provide verification means for the development of theory or numerical simulation.

Theory and numerical simulation are also important means in the study of rock mechanics (Cao et al. 2020b; Zhao et al. 2020a; Zheng et al. 2020). For freeze–thaw damage of rocks, Zhang et al. (2020e) presented an analytical solution for the frost heaving force based on complex variable theory and the power series method; a model describing the dynamic increase factor for the dynamic rock strength corresponding to different strain rates and specimen sizes was given by Ke et al. (2018); Zhang et al. (2020b) derived an elasto-visco-plastic model based on stress functions to describe deformation and damage of water-saturated rocks during the freeze–thaw process; Zhang et al. (2020c) established a damage model which can reflect the characteristics of post-peak strain softening and residual strength; Chen et al. (2020) derived the damage evolution equation of fractured rock; Huang et al. (2020) proposed a novel elastoplastic model to estimate the long-term frost heave and frost damage. In the aspect of numerical simulation, Pu et al. (2020) analyzed the dynamic compressive strength and dynamic elastic modulus of sandstone based on LS-DYNA;
Lin et al. (2020a) established a 3D model considering moisture migration loss to study the characteristics of frost heaving force within joints.

To make a long story short, the above-mentioned achievements provide a reference for the study of this paper. Here, we first carried out the damage experiments of granite samples under freeze–thaw cycles; after that, considering the actual situation of rock masses in high altitude area, especially the different states caused by seasonal changes, the impact compression characteristics of freeze–thawed granite samples were studied under four different states, such as moisture content and temperature difference. It should be noted that no similar studies have been reported so far.

The principle of Split Hopkinson Pressure Bar (SHPB) device

As shown in Fig. 1, the Split Hopkinson Pressure Bar (SHPB) device is mainly composed of gas gun, striker, incident bar, gauge, transmitted bar, momentum bar, etc. In the impact test, the rock sample is placed between the incident bar and the transmitted bar, after adjusting the position and setting the impact pressure, the incident bar is impacted by the pressure released from the gas gun to produce one-dimensional stress wave acting on the sample.

It is assumed that the SHPB device conforms to the mechanical characteristics of one-dimensional bar, then two conditions need to be met during the process of P-wave propagation; that is to say, the cross section of the rod before and after deformation is plane, and the axial force in the rod is evenly distributed. Dynamic mechanical parameters of specimens can be calculated indirectly by the measured voltage in strain gauge in test: stress $\sigma$, strain $\varepsilon$, and strain rate $\dot{\varepsilon}$, which can be expressed as follows (Xie et al. 2014; Wang et al. 2020a; Hassan and Wille 2017; Jia et al. 2021):

$$\sigma = \frac{P_1 + P_2}{2A_0} = \frac{AE}{2A_0} [\varepsilon_i + \varepsilon_r + \varepsilon_t]$$

(1)

$$\varepsilon = \frac{\mu_1 - \mu_2}{l_0} = \frac{c_0}{l_0} \int_0^t [\varepsilon_i - \varepsilon_r - \varepsilon_t] dt$$

(2)

![Typical Split Hopkinson Pressure Bar (SHPB) device](image)

(a) The Composition of a SHPB device

(b) The typical waveforms
\[ \dot{\varepsilon} = \frac{v_1 - v_2}{l_0} = \frac{c_0}{l_0} [\varepsilon_i - \varepsilon_r - \varepsilon_t], \]  

(3)

where \(A\) and \(E\) are cross-sectional area and Young’s modulus of pressure bar, respectively; \(A_0, l_0\) are cross-sectional area and length of granite samples, respectively; \(\varepsilon_i, \varepsilon_r, \text{ and } \varepsilon_t\) are the incident strain signal, reflected strain signal, and transmitted strain signal, respectively; \(c_0\) is the P-wave velocity in the pressure bar; \(v_1\) and \(v_2\) are the velocities at the incident and transmitted specimen faces, respectively; \(P_1\) and \(P_2\) are the forces at the incident and transmitted faces, respectively; \(C_0\) is the one-dimensional longitudinal stress wave velocity of the bar.

In Eqs. (1)–(3), \(v_1, v_2, P_1, P_2, \mu_1, \text{ and } \mu_2\) can be expressed as follows (Hassan and Wille 2017; Jia et al. 2021):

\[
\begin{align*}
\begin{cases}
   v_1 &= c_0 (\varepsilon_i - \varepsilon_r) \\
   v_2 &= c_0 \varepsilon_t
\end{cases} \\
\begin{cases}
   P_1 &= AE (\varepsilon_i + \varepsilon_r) \\
   P_2 &= AE \varepsilon_t
\end{cases} \\
\begin{cases}
   \mu_1 &= c_0 \int_0^t (\varepsilon_i - \varepsilon_r) dt \\
   \mu_2 &= c_0 \int_0^t \varepsilon_t dt
\end{cases}
\]

(4)

(5)

(6)

Sample preparation and test plan

Granite samples with similar properties were selected for the study, which has a medium crystal size, inconspicuous joints, and cracks, and their average compressive strength is 70 MPa. According to the ISRM recommendations, the size of rock samples is \(\varnothing 50 \text{ mm} \times 50 \text{ mm}\), i.e., the length-to-diameter ratio is 1:1. To ensure the accuracy of test results, both ends of the sample were carefully polished to ensure that the parallelism of the upper and lower surfaces is less than 0.05 mm, the flatness of the surface is less than 0.02 mm, the end face is perpendicular to the axis of the sample, and the maximum deviation is not more than 0.25 degrees, and typical samples are shown in Fig. 2.

Granite samples were saturated by a vacuum saturator, and then frozen for 4 h in a thermostat held at \(-30^\circ\text{C}\); finally, the temperature was raised to 20 °C and maintained for 4 h to ensure that samples were completely thawed, and thus, a freeze–thaw cycle was completed. The number of freeze–thaw cycles determined in this paper is 30, 60, 90, and 120, respectively. Considering the actual situation of rock masses in high-altitude area, especially with the seasonal changes, the impact compression characteristics of freeze–thawed granite samples were studied under four different states in this study, such as moisture content and temperature difference. There are five groups of rock samples in each case, and the details of the four cases are as follows:

(1) The compression characteristics of freeze–thawed samples in dry and normal temperature states.
   After freeze–thaw treatment, granite samples were dried and then placed indoors at room temperature, and finally, the impact compression test was carried out using SHPB device (see Fig. 3).

(2) The compression characteristics of freeze–thawed samples in dry and frozen states.
   After freeze–thaw treatment, granite samples were dried and then frozen in a thermostat held at \(-30^\circ\text{C}\).
   When reaching the set-point temperature, samples were taken out from the freeze–thaw tester, and placed in the heat preservation container, and finally, the impact compression test of frozen samples was carried out using SHPB device.
(3) The compression characteristics of freeze–thawed samples in saturated and normal temperature states.

After freeze–thaw treatment, granite samples were saturated in vacuum and soaked in water for 48 h to ensure their complete saturation, and finally, the impact compression test was carried out by using SHPB device.

(4) The compression characteristics of freeze–thawed samples in saturated and frozen states.

After freeze–thaw treatment, granite samples were saturated in vacuum and soaked in water for 48 h to ensure their complete saturation, and then frozen in a thermostat held at –30 °C. When reaching the set-point temperature, samples were taken out from the freeze–thaw tester, and placed in the heat preservation container, and finally, the impact compression test of freeze–thawed samples was carried out using SHPB device.

Analysis of test results

Comparison of impact strength

The impact compressive strength of each group of samples under different states is shown in Fig. 4, and the gas pressure impact on samples is equal to 0.6 MPa. The four states of samples subjected to freeze–thaw treatment are described in Sect. 3. In the same state, the impact compressive strength decreases with the increase of freeze–thaw cycles, and this is mainly due to the continuous migration and accumulation of water in rock samples caused by repeated freeze–thaw cycles, the frost heave stress repeatedly acting on rock pores, and the uneven shrinkage and expansion of different mineral components, eventually leading to the growth of cracks and performance deterioration.

In addition, after 120 freeze–thaw cycles, the degradation degree of average impact strength of samples in four states is 20.17, 25.93, 31.22, and 39.17%, respectively. It can be seen that although the number of freeze–thaw cycles is the same, the deterioration degree is different due to the different state (see Sect. 3) of granite samples. In this study, granite samples in saturated and frozen states display the greatest degree of degradation of average impact strength, while the degree of degradation is the least in dry and normal temperature states; moreover, the degree of degradation ranks second in the dry and frozen states, and it ranks third in saturated and normal temperature states. The possible reasons are as follows:

(1) In dry and normal temperature states, the internal microstructures of granite samples are filled with water, generally called pore water, which transfers compressive stress to crack tip and produces tensile stress when subjected to impact load, and therefore, pore water plays an active role in crack growth, resulting in the decrease of compressive strength of granite samples. In addition, capillary pressure generally exists in the pores and plays a role in adhesively bonding mineral particles. However, the capillary pressure decreases with the increase of water content, when the pore is saturated with water, the crack tip may be in a tensile state of stress, which makes it easier to propagate. Water also weakens the properties of cementitious materials in rocks, which is also unfavorable to the impact strength.

(2) In the dry and frozen states, rock sample belongs to a single-phase medium, the mineral particles contract when cooled, leading to the growth of cracks. On the other hand, when the rock is frozen, the bond strength decreases accordingly.

(3) In saturated and frozen states, the shrinkage of mineral particles and crystals leads to crack propagation; moreover, water turns into ice, resulting in an increase in volume, and these two factors are unfavorable to the impact strength of samples. Moreover, the interaction between the shrinkage of mineral particles, crystals, and the volume expansion of water causes strong tensile stress, and promotes crack propagation.

To study the relationship between impact strength and freeze–thaw cycles under the same weathering state, we take the freeze–thaw times as the independent variable and the impact compressive strength as the dependent variable, and then, Eq. (7) can be obtained

\[ \sigma = an^2 + bn + c, \]
where $\sigma$ is impact compressive strength; $n$ is freeze–thaw cycles; $a$, $b$, and $c$ are arbitrary coefficients, and the values are shown in Table 1.

The relationship between impact compressive strength and freeze–thaw cycles is shown in Fig. 5, which further shows that although the conditions are different, the variation rules are similar. In dry and normal temperature states, the impact strength of granite samples is always the largest with the increase of freeze–thaw cycles. In saturated and frozen states, the impact strength of granite samples is always the minimum. Generally speaking, the impact strength of granite samples has the smallest dispersion in saturated and normal temperature states, and the largest dispersion in dry and normal temperature states. As the number of freeze–thaw cycles increases, the deceleration of impact strength gradually slows down, and showing that the slope of curves slightly decreases (see Fig. 5a–c); however, the deceleration of impact strength increases slowly in Fig. 5d, and showing that the slope of curves slightly increases.

**The stress–strain characteristics**

Figure 6 shows the typical stress–strain curve of granite samples under impact load, the results depict that the stress–strain curve can be divided into elastic stage, yield stage, and failure stage, and has no obvious compaction stage, and displays a linear increase state initially. In addition, after entering into the yield stage, the structures with lower strength in samples are initially cracked and destroyed, and leading to the damage of surrounding structure in high stress environment, and then, macro-cracks are generated until the sample is destroyed.

### Table 1 Arbitrary coefficient value

| Different states                     | $A \times 10^{-4}$ | $b$   | $c$    |
|-------------------------------------|--------------------|-------|--------|
| Dry and normal temperature states   | 8.25               | 0.45  | 221.09 |
| Dry and frozen states               | 1.19               | −0.52 | 151.48 |
| Saturated and normal temperature states | 8.10               | −0.50 | 192.53 |
| Saturated and frozen states         | −1.19              | −0.31 | 141.08 |

![Fig. 5](image-url) The relationship between impact compressive strength and freeze–thaw cycles
It can be seen from Fig. 6a–d that the elastic modulus of granite gradually decreases with increase of freeze–thaw cycles. The reason may be that the frost heaving force compresses the pore structure, which leads to the initiation and growth of micro-cracks, resulting in the destruction of the internal structure. In addition, the repeated change of temperature (−30 °C, +20 °C) leads to the continuous conversion of shrinkage and expansion of cementitious materials, resulting in the gradual deterioration of granite properties. Moreover, the dissolution and erosion of cementitious materials during the melting process also lead to the formation of cracks, and therefore, the elastic modulus of granite decreases under the impact load, and the decreasing range increases with the increase of freeze–thaw cycles.

As shown in Fig. 7, the elastic modulus also shows obvious differences in different states under the same freeze–thaw cycles. Generally speaking, the elastic modulus of granite has maximum value in saturated and frozen states, except for the specimens without freeze–thaw cycles, and second largest value in saturated and normal temperature states. In addition, Fig. 7 also shows that the value of elastic modulus is relatively small in dry and normal temperature states as well as dry and frozen states. From a theoretical point of view, the minimum value of elastic modulus should be obtained in dry and normal temperature states; however, considering the discreteness of samples, the comparison of the values of elastic modulus given by the black and blue curves in Fig. 7 shows that the results are a little different from the theory. In a word, the possible reasons are as follows:

1. Water expands when it freezes, and the mineral particles shrink when cooled, leading to crack propagation and strength degradation. In saturated and frozen states, micro-cracks have become incompressible due to the existence of ice, the crack propagates directly without compaction under impact load, so the strain before failure is relatively small, and the elastic modulus becomes larger.
In saturated and normal temperature states, cracks are filled with water which plays a positive role in crack initiation, leading to the deterioration of mechanical properties of granite samples. When subjected to impact load, micro-cracks have become difficult to close due to the existence of water, and propagate.
directly, and therefore, samples are destroyed without larger strain. However, a small amount of water will overflow under impact load, so the elastic modulus is still lower than that in saturated and frozen states. 

(3) In dry and normal temperature states, there is no water in micro-cracks which can be compressed under impact load, and therefore, the deformation is relatively larger, resulting in a smaller elastic modulus. 

(4) In dry and frozen states, low temperature reduces the cohesion of the internal structure of granite samples and increases its brittleness, compared with the dry and normal temperature state, the granite sample is relatively difficult to deform and more prone to brittle failure under the same load condition.

**Influence analysis of freeze–thaw cycles**

Four different states are considered to study the effect of freeze–thaw cycles on the mechanical properties of granite samples; in this section, the freeze–thaw influence factors are proposed to characterize the influence of degree of freeze–thaw cycles, as shown in Eq. (8)

$$\omega = \frac{\sigma_0 - \sigma_n}{n}, \quad (8)$$

where $\omega$ is the freeze–thaw influence factors; $\sigma_0$ is the impact compressive strength of rock samples without freeze–thaw cycles; $\sigma_n$ is the impact compressive strength of rock samples after the nth freeze–thaw cycle; $n$ is the number of freeze–thaw cycles.

According to Eq. (8), the freeze–thaw influence factors of granite samples in four different states are shown in Fig. 8. The results show that the freeze–thaw influence factor has the maximum value in saturated and frozen states, and the minimum value in dry and normal temperature states. One of the reasons may be that, as the increase of freeze–thaw cycles, the damage of rock pore structures increases gradually, if the pore structures are filled with medium, such as water, ice, etc., the crack propagation is promoted when subjected to impact load, and the degree of deterioration of impact strength increases with increase of porosity. It can also be seen from Fig. 8 that the freeze–thaw influence factor in dry and frozen states is larger than that in dry and normal temperature states, and this is mainly due to the increase of porosity caused by freeze–thaw cycles, leading to the increase of shrinkage of mineral particles when cooled, and therefore, the impact strength decreases correspondingly and the freeze–thaw influence factor becomes larger. Finally, it can be concluded that water and low temperature improve the effect of freeze–thaw cycles on the dynamic mechanical properties of granite samples in this study.

**Conclusions**

The impact strength of granite samples deteriorates with the increase of freeze–thaw cycles in the same state. For samples in different states, although the number of freeze–thaw cycles is equal, the degree of deterioration of the impact strength is different. The stress–strain curves of granite samples are generally similar to each other in four different states, there is no obvious compaction stage of micro-cracks, and the curves directly enter into the elastic, yield, and failure stages. 

For granite samples in the same state, when subjected to impact load, the dynamic elastic modulus decreases with the increase of freeze–thaw cycles; however, the degree of decrease is different for different states. Under the same freeze–thaw cycles, the dynamic elastic modulus from large to small is generally as follows: samples in saturated and frozen states, samples in saturated and normal temperature states, samples in dry and frozen states, and samples in dry and normal temperature states.

Under the same freeze–thaw cycles, the results show that the deterioration of mechanical properties of granite samples is different in four different weather states, and the order of the freeze–thaw influence factors from large to small is as follows: samples in saturated and frozen states, samples in saturated and normal temperature states, samples in dry and frozen states, as well as samples in dry and normal temperature states. Therefore, water and low temperature improve the effect of freeze–thaw cycles on the dynamic mechanical properties of granite samples.

**Acknowledgements** This paper gets its funding from Project (Grant NO. Z020015) supported by Open Research Fund of State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock
and Soil Mechanics, Chinese Academy of Sciences; Project (Grant No. 52174088, No. 42077249) supported by National Natural Science Foundation of China; Project (Grant No. 2019YFC0605304) supported by the National Key R&D Program of China. The authors wish to acknowledge these supports.

**Author contributions** BK: conceptualization, methodology, resources, data curation, writing—original draft, and funding acquisition. CZ: conceptualization, methodology, resources, writing—review and editing, and funding acquisition. CL: investigation, writing—review and editing, and data curation. LD: conceptualization, methodology, resources, and writing—review and editing. NL: conceptualization, methodology, resources, and writing—review and editing. YW: methodology, writing—review and editing, and funding acquisition. HL: investigation, writing—review and editing, and data curation.

**Declarations**

**Conflict of interest** The authors declared that there is no conflict of interest.

**References**

Abdolghanzadeh K, Hosseini M, Saghaifyazdi M (2020) Effect of freezing temperature and number of freeze–thaw cycles on mode I and mode II fracture toughness of sandstone. Theor Appl Fract Mech 105:102428

Bost M, Pouya A (2017) Stress generated by the freeze–thaw process in open cracks of rock walls: empirical model for tight limestone. Bull Eng Geol Environ 76:1491–1505

Cao R, Wang C, Yao R, Hu T, Lei D, Lin H, Zhao Y (2020a) Effects of cyclic freeze–thaw treatments on the fracture characteristics of sandstone under different fracture modes: Laboratory testing. Theor Appl Fract Mech 109:102738

Cao R, Yao R, Hu T, Wang C, Li K, Meng J (2020b) Failure and mechanical behavior of transversely isotropic rock under compression-shear tests: laboratory testing and numerical simulation. Eng Fract Mech 241:107389

Cao R, Yao R, Meng J, Lin Q, Lin H, Li S (2020c) Failure mechanism of non-persistent jointed rock-like specimens under uniaxial loading: Laboratory testing. Int J Rock Mech Min Sci 132:104341

Çelik MY (2017) Water absorption and P-wave velocity changes during freeze–thaw action in alpine rocks in the European Alps during a nine year monitoring period. Geomorphology 296:113–131

Fan X, Yang ZJ, Li KH (2021a) Effects of the lining structure on mechanical and fracturing behaviors of four-arc shaped tunnels in a jointed rock mass under uniaxial compression. Theor Appl Fract Mech 112:102887

Fan X, Jiang XD, Liu YX, Lin H, Li KH, He ZM (2021b) Local stress distribution and evolution surrounding flaw and opening within rock block under uniaxial compression. Theor Appl Fract Mech 112:102914

Fang X, Xu J, Wang P (2018) Compressive failure characteristics of yellow sandstone subjected to the coupling effects of chemical corrosion and repeated freezing and thawing. Eng Geol 233:160–171

Freire-Lista DM, Fort R (2017) Exfoliation microcracks in building granite. Implications for anisotropy. Eng Geol 220:85–93

Freire-Lista DM, Fort R, Varas-Muriel MJ (2015) Freeze–thaw fracturing in building granites. Cold Reg Sci Technol 113:40–51

Gorbatsevich FF (2003) Decompaction mechanism of deep crystal-line rocks under stress relief. Tectonophysics 370:121–128

Han T, Wang X, Li Z, Li D, Xing F, Han N (2020) Laboratory investigation of the mode-I fracture of sandstone caused by a combination of freeze–thaw cycles and chemical solutions. Bull Eng Geol Environ 79:3689–3706

Hashemi M, Goudarzi MB, Jamshidi A (2018) Experimental investigation on the performance of Schmidt hammer test in durability assessment of carbonate building stones against freeze–thaw weathering. Environ Earth Sci 77:684

Hassan M, Wille K (2017) Experimental impact analysis on ultra-high performance concrete (UHPC) for achieving stress equilibrium (SE) and constant strain rate (CSR) in Split Hopkinson pressure bar (SHPB) using pulse shaping technique. Constr Build Mater 144:747–757

Huang S, Lu Z, Ye Z, Xin Z (2020) An elastoplastic model of frost deformation for the porous rock under freeze–thaw weathering. Eng Geol 278:105820

Ivanikina TI, Zel IY, Petrozulek M, Rodkin MV, Matveev MA, Lokajicek T (2020) Elastic anisotropy, permeability, and freeze–thaw cycling of rapakivi granite. Int J Rock Mech Min Sci 136:104541

Jia H, Ding S, Zi F, Dong Y, Shen Y (2020) Evolution in sandstone pore structures with freeze–thaw cycling and interpretation of damage mechanisms in saturated porous rocks. CATENA 195:104915

Jia SQ, Wang FS, Zhou JJ, Jiang ZP, Xu B (2021) Study on the mechanical performances of carbon fiber/epoxy composite material subjected to dynamical compression and high temperature loads. Compos Struct 258:113421

Ke B, Zhou K, Xu C, Deng H, Li J, Bin F (2018) Dynamic mechanical property deterioration model of sandstone caused by freeze-thaw weathering. Rock Mech Rock Eng 51:2791–2804

Ke B, Zhang J, Deng H, Yang X (2020) Dynamic characteristics of sandstone under coupled static-dynamic loads after freeze–thaw cycles. Appl Sci 10:3351

Kellerer-Pirklbauer A (2017) Potential weathering by freeze–thaw action in alpine rocks in the European Alps during a nine year monitoring period. Geomorphology 296:113–131

Kellerer-Pirklbauer A (2017) Potential weathering by freeze–thaw action in alpine rocks in the European Alps during a nine year monitoring period. Geomorphology 296:113–131

Langman JB, Blowes DW, Amos RT, Atherton C, Wilson D, Smith L, Sego DC, Sinclair SA (2017) Influence of a tundra freeze–thaw cycle on sulfide oxidation and metal leaching in a low sulfur, granitic waste rock. Appl Geochem 76:9–21

Li K, Li M, Zhang D, Liu C, Ma D (2020) Effect of moisture content on energy mechanism of freezing-thawing treated sandstone under uniaxial static compression. KSCE J Civil Eng 23(5):2074–2082

Li XS, Peng K, Peng J, Hou D (2021b) Experimental investigation of the mode-I fracture of sandstone caused by a combination of freeze–thaw cycles and chemical solutions. Bull Eng Geol Environ 79:3689–3706

Li XS, Peng K, Peng J, Hou D (2021a) Effect of thermal damage on mechanical behavior of a fine-grained sandstone. Arab J Geosci 14:1212. https://doi.org/10.1007/s12517-021-07607-0

Li XS, Peng K, Peng J, Hou D (2021b) Experimental investigation of cyclic wetting-drying effect on mechanical behavior of a...
medium-grained sandstone. Eng Geol 293:106335. https://doi.org/10.1016/j.enggeo.2021.106335
Li XS, Yang S, Wang YM, Nie W, Liu ZF (2021c) Macro-micro response characteristics of surrounding rock and overlying strata toward the transition from open-pit to underground mining. Geofluids 2021:1–18. https://doi.org/10.1155/2021/5582218
Lin H, Lei D, Yong R, Jiang C, Du S (2020a) Analytical and numerical analysis for frost heaving stress distribution within rock joints under freezing and thawing cycles. Environ Earth Sci 79(12):305
Lin H, Lei D, Zhang C, Wang Y, Zhao Y (2020b) Deterioration of non-persistent rock joints: a focus on impact of freeze–thaw cycles. Int J Rock Mech Min Sci 135:104515
Lin H, Zhang X, Cao R, Wen Z (2020c) Improved nonlinear Burgers shear creep model based on the time-dependent shear strength for rock. Environ Earth Sci 79:149
Liu C, Deng H, Chen X, Xiao D, Li B (2020a) Impact of rock samples size on the microstructural changes induced by freeze–thaw cycles. Rock Mech Rock Eng 53:5293–5300
Liu T, Zhang C, Cao P, Zhou K (2020b) Freeze–thaw damage evolution of fractured rock mass using nuclear magnetic resonance technology. Cold Reg Sci Technol 170:102951
Liu Y, Cai Y, Huang S, Guo Y, Liu G (2020c) Effect of water saturation on uniaxial compressive strength and damage degree of clay-bearing sandstone under freeze–thaw. Bull Eng Geol Environ 79:2021–2036
Liu C, Wang D, Wang Z, Ke B, Li P, Yu S (2021) Dynamic splitting tensile test of granite under freeze–thaw weathering. Soil Dyn Earthq Eng 140:106411
Lu Y, Li X, Han Y, Wu J (2021) Mechanical properties of rock samples with a single natural weak plane after freeze–thaw action. Cold Reg Sci Technol 181:103179
Mardoukhi A, Mardoukhi Y, Hokma M, Kuokkala V (2021) Effects of test temperature and low temperature thermal cycling on the dynamic tensile strength of granite rocks. Rock Mech Rock Eng 54:443–454
Mousavi SZZ, Tavakoli H, Moarefvand P, Rezaei M (2020) Micro-structural, petro-graphical and mechanical studies of schist rocks under the freezing-thawing cycles. Cold Reg Sci Technol 174:103039
Pan Z, Zhou K, Gao R, Jiang Z, Yang C, Gao F (2020) Research on the pore evolution of sandstone in cold regions under freeze–thaw weathering cycles based on NMR. Geofluids 2020:8849444
Pápay Z, Török Á (2015) Effect of thermal and freeze–thaw stress on the mechanical properties of porous limestone. Periodica Polytechnica Civil Eng 62(2):423–428
Pu QS, Huang JH, Zeng FL, Luo Y, Li XP, Zhou JX, Zheng SL (2020) Study on long-term dynamic mechanical properties and degradation law of sandstone under freeze–thaw cycle. Shock Vib 2020:827169
Sarici DE, Ozdemir E (2018) Determining point load strength loss from porosity, Schmidt hardness, and weight of some sedimentary rocks under freeze–thaw conditions. Environ Earth Sci 77(3):62
Shen YJ, Yang GS, Rong TL, Liu H, Lu WY (2016) Proposed scheme for freeze–thaw cycle tests on rock. Chin J Geotech Eng 38(10–11):1775–1782 (In Chinese)
Shen Y, Yang H, Xi J, Yang Y, Wang Y, Wei X (2020) A novel shearing fracture morphology method to assess the influence of freeze–thaw actions on concrete–granite interface. Cold Reg Sci Technol 169:102900
Sinclair SA, Pham N, Amos RT, Sego DC, Smith L, Blowes DW (2015) Influence of freeze–thaw dynamics on internal geochemical evolution of low sulfide waste rock. Appl Geochem 61:160–174
Wang P, Xu J, Liu S, Wang H, Liu S (2016) Static and dynamic mechanical properties of sedimentary rock after freeze–thaw or thermal shock weathering. Eng Geol 210:148–157
Wang P, Xu J, Fang X, Wang P, Zheng G, Wen M (2017) Ultrasonic time-frequency method to evaluate the deterioration properties of rock suffered from freeze–thaw weathering. Cold Reg Sci Technol 143:13–22
Wang SR, Chen YL, Ni J, Zhang MD, Zhang H (2019a) Influence of freeze–thaw cycles on engineering properties of tontable: examples from China. Adv Civil Eng 2019:1–12. https://doi.org/10.1155/2019/3418134
Wang Y, Feng W, Wang H, Han J, Li C (2019b) Geomechanical and acoustic properties of intact granite subjected to freeze–thaw cycles during water-ice phase transformation in beizhan’s open pit mine slope, Xinjiang, China. Water 11(11):2309
Wang FZ, Liu SY, Cao L (2020a) Research on dynamic compressive behaviors of marble under high strain rates with split Hopkinson pressure bar. J Struct Geol 138:104905
Wang Y, Han QJ, Li CH (2020b) Acoustic emission and CT investigation on fracture evolution of granite containing two flaws subjected to freeze–thaw and cyclic uniaxial increasing-amplitude loading conditions. Constr Build Mater 260:119769
Wang D, Chen G, Jian D, Zhu J, Lin Z (2021a) Shear creep behavior of red sandstone after freeze–thaw cycles considering different temperature ranges. Bull Eng Geol Environ 80:2349–2366
Wang Y, Gao SH, Li CH, Han QJ (2021b) Energy dissipation and damage evolution for dynamic fracture of marble subjected to freeze–thaw and multiple level compressive fatigue loading. Int J Fatigue 142:105927
Xiao Y, Li C, Cao J, Wang Y, Hou Z, Hu N (2020) Investigation of the effects of freeze–thaw cycles on geomechanical and acoustic characteristics of tuff specimens under different stress paths. Adv Civil Eng 2020:6689181
Xie YJ, Fu Q, Zheng KR, Yuan Q, Song H (2014) Dynamic mechanical properties of cement and asphalt mortar based on SHPB test. Constr Build Mater 70:217–225
Xu J, Liu Y, Ni Y (2019) Hierarchically weighted rough-set genetic algorithm of rock slope stability analysis in the freeze–thaw mountains. Environ Earth Sci 78:227
Yang C, Zhou K, Xiong X, Deng H, Pan Z (2021a) Experimental investigation on rock mechanical properties and infrared radiation characteristics with freeze–thaw cycle treatment. Cold Reg Sci Technol 183:103232
Yang X, Jiang A, Zhang F (2021b) Research on creep characteristics and variable parameter-based creep damage constitutive model of gneiss subjected to freeze–thaw cycles. Environ Earth Sci 80:7
Zhang CY, Pu CZ, Cao RH, Jiang TT, Huang G (2019) The stability and roof-support optimization of roadways passing through unfavorable geological bodies using advanced detection and monitoring methods, among others, in the Sammenxia Bauxite Mine in China’s Henan Province. Bull Eng Geol Environ 78(T7):5087–5099
Zhang CY, Wang YX, Jiang TT (2020a) The propagation mechanism of an oblique straight crack in a rock sample and the effect of osmotic pressure under in-plane biaxial compression. Arab J Geosci 13(15):736
Zhang CY, Zou P, Wang YX, Jiang TT, Lin H, Cao P (2020b) An elasto-visco-plastic model based on stress functions for deformation and damage of water-saturated rocks during the freeze–thaw process. Constr Build Mater 250:118862
Zhang H, Meng X, Yang G (2020c) A study on mechanical properties and damage model of rock subjected to freeze–thaw cycles and confining pressure. Cold Reg Sci Technol 174:03056
Zhang J, Deng H, Deng J, Guo H (2020d) Influence of freeze–thaw cycles on the degradation of sandstone after loading and unloading. Bull Eng Geol Environ 79:1967–1977
Zhang J, Zhang X, Fu H, Wu Y, Huang Z, Chen D (2020e) An analytical solution for the frost heaving force considering the freeze–thaw damage and transversely isotropic characteristics of the surrounding rock in cold-region tunnels. Adv Civil Eng 2020:6654778
Zhang CY, Wang YX, Ruan H, Ke B, Lin H (2021) The strain characteristics and corresponding model of rock materials under uniaxial cyclic load/unload compression and their deformation and fatigue damage analysis. Arch Appl Mech 91:2481–2496. https://doi.org/10.1007/s00419-021-01899-0

Zhao H, Zhang X, Han G, Chen H (2019) Experimental investigation on the physical and mechanical properties deterioration of oil shale subjected to freeze–thaw cycles. Arab J Geosci 12:531

Zhao YL, Zhang CS, Wang YX, Lin H (2020a) Shear-related roughness classification and strength model of natural rock joint based on fuzzy comprehensive evaluation. Int J Rock Mech Min Sci 137:104550

Zhao YL, Zhang LY, Liao J, Wang WJ, Liu Q, Tang L (2020b) Experimental study of fracture toughness and subcritical crack growth of three rocks under different environments. Int J Geomech 20(8):04020128

Zheng Y, Chen CX, Liu TT, Ren ZH (2021) A new method of assessing the stability of anti-dip bedding rock slopes subjected to earthquake. Bull Eng Geol Environ 80:3693–3710

Zheng Y, Chen CX, Meng F, Liu T, Xia K (2020) Assessing the stability of rock slopes with respect to flexural toppling failure using a limit equilibrium model and genetic algorithm. Comput Geotech 124:103619

Zhou K, Li B, Li J, Deng H, Bin F (2015) Microscopic damage and dynamic mechanical properties of rock under freeze–thaw environment. Trans Nonferr Metals Soc China 25(4):1254–1261

Zhou XP, Niu Y, Zhang JZ, Shen XC, Zheng Y, Berto F (2018) Experimental study on effects of freeze-thaw fatigue damage on the cracking behaviors of sandstone containing two unparallel fissures. Fatigue Fract Eng Mater Struct 42(6):1322–1340

Zhou Z, Zhan H, Hu J, Ren C (2019) Characteristics of unloading creep of tuffaceous sandstone in east Tianshan tunnel under freeze–thaw cycles. Adv Mater Sci Eng 2019:7547564

Ziegler M, Loew S, Bahat D (2014) Growth of exfoliation joins and near-surface stress orientations inferred from fractographic markings observed in the upper Aar valley (Swiss Alps). Tectonophysics 626:1–20

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.