Study on Changes in Physical and Mechanical Properties and Integrity Decay of Sandstone Subjected to Freeze–Thaw Cycling

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Abstract: To investigate the effects of long-term freeze–thaw cycles on the physical and mechanical properties as well as the attenuation trend of rocks, this study conducted saturated freeze–thaw tests on coarse sandstone and fine sandstone samples collected from the slopes of Muli Coal Mine in Qinghai Province. The samples underwent different numbers of freeze–thaw cycles, and their porosity, longitudinal wave velocity, and uniaxial compression strength were studied. The variations in the physical and mechanical properties of the two types of sandstone with respect to the number of freeze–thaw cycles were analyzed. Take uniaxial compressive strength (UCS) as the integrity index, and decay laws of rock integrity were analyzed based on the decay equation suggested in previous studies. We found that the decay index \( \lambda \), which is commonly assumed to be constant, varies with the number of freeze–thaw cycles. Furthermore, the \( \lambda \) values varied between different rock types. For fine sandstone, the \( \lambda \) decreases with an increase in the number of freeze–thaw cycles, ranging from 0.00385 to 0.005. However, for coarse sandstone, the \( \lambda \) initially decreases and then increases with an increase in the number of freeze–thaw cycles. The range of \( \lambda \) for coarse sandstone is between 0.00376 and 0.00481. Finally, we established a relationship between the decay index, porosity, and longitudinal wave velocity in the fine sandstones. This relationship provides a more straightforward way to evaluate the integrity of fine sandstones subjected to different numbers of freeze–thaw cycles.

Keywords: rock; freeze–thaw cycling; decay equation; decay index \( \lambda \); uniaxial compressive strength (UCS)

1. Introduction

Investigations conducted in mountainous areas such as the Alps and the South-North Polar regions [1,2] have revealed the detrimental effects of long-term freeze–thaw cycling on rocks. This natural weathering process leads not only to the rupture of surface rocks and the accumulation of debris but also increases the occurrence of hazardous events such as rock falls and landslides. Over an extended period, in conjunction with other weathering processes, these phenomena contribute to ongoing changes in the topography and geomorphology of cold regions [3]. Furthermore, during engineering construction activities in cold areas, various rock elements, including rock side-slopes, tunnel-wall rocks, and rock materials used for construction purposes (e.g., carvings, wall surfaces, and ground linings), are susceptible to damage caused by freeze–thaw cycling [4–9]. Therefore, gaining a comprehensive understanding of the alterations in the physical and mechanical properties of rocks subjected to freeze–thaw cycles is crucial not only for elucidating the evolution of topography and geomorphology but also for facilitating effective engineering construction practices in cold regions.

Since the 1950s, many experiments of rocks under F–T cycling have been carried out [10–19]. The results further confirmed that the physical and mechanical properties of
rocks deteriorate with F–T cycles. Based on the results of 10 different rocks subjected to F–T cycling, Mutlutürk [20] found that if Shore hardness (SH) was the rock integrity index, there is a relationship between the rock integrity index and the number of F–T cycles.

\[ I_N = I_0 e^{-\lambda N} \]  

(1)

where, \( \lambda \) is the decay index, \( I_0 \) is the rock initial integrity, and \( I_N \) is the integrity after \( N \) cycles of freeze–thaw (F–T). Since then, scholars [21–31] have adopted different physical and mechanical indices of various rocks under F–T cycles as integrity to validate this equation. Partial data are summarized in Table 1. Considering that UCS is a more meaningful mechanical indicator for engineering purposes, this study uses UCS as integrity.

When determining \( \lambda \), the usual method is to measure the integrity before and after it is subjected to different F–T cycles, and then based on Equation (1), regression analysis is used to obtain the \( \lambda \) [21–31]. Another approach is to establish a relationship between the initial physical and mechanical indices of the rock and the decay index and use this to estimate the decay index. For example, Yavuz [32] calculated the decay index based on the initial integrity and porosity, while Huang et al. [33] calculated the decay index based on the initial porosity, elastic modulus, and Brazilian tensile strength (BTS). There is an implicit prerequisite, i.e., \( \lambda \) is considered as a constant in the whole process of F–T cycling, which does not conform to the observed phenomena in the experiments [12,34]. It is reasonable to consider that \( \lambda \) varies with the number of F–T cycles. The relationships between \( \lambda \) and the F–T cycle numbers are likely to be different.

To investigate the effects of long-term freeze–thaw cycles on the physical and mechanical properties as well as the attenuation trend of rocks, the present authors investigated the changes in physical and mechanical properties of two sandstones subjected to F–T cycling. Taking uniaxial compressive strength (UCS) as the integrity, the decay equation and the decay index of the rock integrity in terms of F–T cycling were studied. For fine sandstone, we observed that the decay index gradually decreases with an increase in the number of freeze–thaw cycles. Furthermore, it exhibits a good fitting relationship with the longitudinal wave velocity. This relationship provides a more straightforward way to evaluate the integrity of fine sandstones subjected to different numbers of freeze–thaw cycles.
Table 1. Different integrity indexes and corresponding decay index $\lambda$.

<table>
<thead>
<tr>
<th>Author</th>
<th>Times of F-T Cycles</th>
<th>Rock Type</th>
<th>Uniaxial Compressive Strength (UCS)</th>
<th>Brazilian Tensile Strength (BTS)</th>
<th>Point Load Strength (PLS)</th>
<th>P-Wave Velocity ($V_p$)</th>
<th>Effective Porosity ($n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\lambda$  $R^2$</td>
<td>$\lambda$  $R^2$</td>
<td>$\lambda$  $R^2$</td>
<td>$\lambda$  $R^2$</td>
<td>$\lambda$  $R^2$</td>
</tr>
<tr>
<td>Akin &amp; Özsan [21]</td>
<td>50</td>
<td>Yellow</td>
<td>A 0.0024 0.884</td>
<td>B 0.0047 0.96</td>
<td></td>
<td>$-0.0005$ 0.303</td>
<td></td>
</tr>
<tr>
<td>Yavuz [22]</td>
<td>50</td>
<td>andesite</td>
<td>0.003 0.98</td>
<td></td>
<td>$0.0014$ 0.89</td>
<td>$-0.0036$ 0.93</td>
<td></td>
</tr>
<tr>
<td>Jamshidi et al. [23]</td>
<td>30</td>
<td>Travertine-I</td>
<td>0.024 0.955</td>
<td>Limestone-II</td>
<td>0.002 0.91</td>
<td>Marble-I</td>
<td>0.003 0.899</td>
</tr>
<tr>
<td>Jamshidi et al. [24]</td>
<td>60</td>
<td>Gerdoee travertine</td>
<td>0.003 0.9525</td>
<td></td>
<td>$0.004$ 0.992</td>
<td>$0.004$ 0.9405</td>
<td>$0.002$ 0.9703</td>
</tr>
<tr>
<td>Ghobadi et al. [25]</td>
<td>60</td>
<td>Sandstone</td>
<td>A 0.0038 0.9921</td>
<td>B 0.00136 0.9878</td>
<td>C 0.002 0.9484</td>
<td>CG 0.00349 0.8754</td>
<td>Tr 0.00341 0.9814</td>
</tr>
<tr>
<td>Ghobadi et al. [26]</td>
<td>70</td>
<td>Tuff</td>
<td>F.1.2 0.00357 0.988</td>
<td>F.3.A 0.00709 0.879</td>
<td>E.D 0.00368 0.959</td>
<td>VAR.M 0.00249 0.971</td>
<td>V.B.1 0.01445 0.963</td>
</tr>
</tbody>
</table>

Notes: $R^2$ is the determined coefficient.
2. Materials and Methods

The rocks used for the experiment were taken from the slope of the Muji open-pit coal mine in Qinghai, and consist of two varieties of sandstone, one is coarse and the other is fine. The rock samples were processed into standard cylindrical specimens with a diameter of 50 mm and a height of 100 mm, meeting the requirements of the International Society for Rock Mechanics for a height-to-diameter ratio of 2.0~2.5. The processing accuracy followed the relevant requirements of Standard for Test Methods of Engineering Rock mass [35] for uniaxial compressive-strength test specimens. The processed standard specimens were observed and initially selected, and rock samples with visible structural inhomogeneity and defects were screened out. The fine and coarse sandstone samples were numbered separately, with 20 samples for each type of sandstone.

According to the regulations in the Code of Test Methods of Rock for Highway Engineering [36], making reference to the temperature and time setting conditions in previous studies [13,24], the negative temperature in this test was set as \(-25^\circ C\), the duration time was 8 h, the temperature for thaw was +25 \(^\circ\)C, also for 8 h, i.e., one freeze–thaw cycle takes 16 h. The freeze–thaw test was carried out using a freeze–thaw cycling test device XT5405FSC. During freezing, the rock specimens were wrapped up with plastic film so as to keep the moisture content unchanged; and when thawing, the rock specimens were soaked in distilled water.

In order to study the influence of freeze–thaw cycle numbers upon the physical and mechanical properties, the porosity, the velocity of longitudinal wave and the uniaxial compressive strength were measured individually after the rock specimens experienced 0, 30, 60, 90 and 120 freeze–thaw cycles. The variations in these parameters were analyzed. The testing methodologies were as follows.

Equation (2) is used to calculate the porosity:

\[
n = \frac{m_s - m_d}{m_s - m_w} \times 100\%
\]

where, \(n\) denotes the rock porosity \%;

\(m_s\) denotes the rock mass after saturation after different number of freeze–thaw cycles, g;

\(m_d\) is the dry rock mass, g;

\(m_w\) is the rock mass-in-water after different number of freeze–thaw cycles, g.

A digital ultrasonic instrument (RSM-SY5(N)) was used to measure the velocity of longitudinal wave of the saturated rock specimens after a certain number (0, 30, 60, 90, 120) of freeze–thaw cycles.

The multi-functional electro-hydraulic-servo rock mechanical testing system manufactured by the MTS Company was used to perform the uniaxial compressive-strength tests of rock specimens after freeze–thaw cycles. Testing procedures are referred to the Chinese codes of testing method for engineering rock mass [35]. MTS Equipment with circumferential sensors can detect the circumferential strain in rock axial compression so that Poisson’s ratio can be obtained.

3. Results and Discussion

3.1. Changes in Porosity

It can be seen from Table 2 that the porosity of two sandstones increases with the increase in the number of freeze–thaw cycles. For instance, the porosity of fine sandstone specimen No. 2-20 increases from 1.63% to 3.33% after 120 freeze–thaw cycles, with an increase of 104%; while for the porosity of coarse sandstone specimen No. 1-19, an increase of 82% was observed from 1.92% to 3.49% after 120 cycles.

The increase in porosity is likely attributed to ice formation in the specimens. On the one hand, when temperature decreases, pore water in rocks can gradually freeze to ice, producing 9% of the volume expansion. On the other hand, under the action of the temperature gradient, the unfrozen water films migrate and segregation ice forms [37–41].
Under the action of the above two causes, pores in rocks are bound to increase in forms of in situ expansion or even cracks. When temperature rises, moisture gradually infiltrates into the newly formed micro-cracks or expanded pores, causing even more serious expansion or cracking during freezing in the next cycle. Accordingly, freeze–thaw cycles cause the above function to occur repeatedly, thereby leading to a continuous increase in rock porosity.

### Table 2. Porosity of sandstone specimens (%) subjected to different number of freeze–thaw cycles.

<table>
<thead>
<tr>
<th>Sandstone Variety</th>
<th>Specimen No.</th>
<th>Time of Freeze–Thaw Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Fine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-5</td>
<td>2.113</td>
<td>2.438</td>
</tr>
<tr>
<td>2-20</td>
<td>1.628</td>
<td>1.904</td>
</tr>
<tr>
<td>2-22</td>
<td>1.449</td>
<td>1.678</td>
</tr>
<tr>
<td>2-23</td>
<td>1.321</td>
<td>1.574</td>
</tr>
<tr>
<td>Mean</td>
<td>1.628</td>
<td>1.899</td>
</tr>
<tr>
<td>Coarse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-19</td>
<td>1.916</td>
<td>2.379</td>
</tr>
<tr>
<td>1-21</td>
<td>2.444</td>
<td>2.954</td>
</tr>
<tr>
<td>1-23</td>
<td>1.727</td>
<td>2.687</td>
</tr>
<tr>
<td>1-32</td>
<td>1.606</td>
<td>2.089</td>
</tr>
<tr>
<td>Mean</td>
<td>1.923</td>
<td>2.527</td>
</tr>
</tbody>
</table>

### 3.2. Changes in Velocity of Longitudinal Wave

It can be seen from Table 3 that the velocity of the longitudinal wave of two sandstones decreases with the increase in the number of freeze–thaw cycles. There are apparent differences in the varying amplitudes of the two rocks. The average velocity of the longitudinal wave of the fine sandstone specimen decreased from 3821 m/s to 2990 m/s after 120 freeze–thaw cycles, with a decrease of 21.8%, while coarse sandstone specimens decreased from 3642 m/s to 3116 m/s, with a decrease of 14.4%.

### Table 3. Sandstone specimen velocity of longitudinal wave (m/s) after undergoing the different times of freeze–thaw cycles.

<table>
<thead>
<tr>
<th>Sandstone Variety</th>
<th>Specimen No.</th>
<th>Time of Freeze–Thaw Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Fine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-5</td>
<td>3818</td>
<td>3704</td>
</tr>
<tr>
<td>2-20</td>
<td>3705</td>
<td>3607</td>
</tr>
<tr>
<td>2-22</td>
<td>3949</td>
<td>3871</td>
</tr>
<tr>
<td>2-23</td>
<td>3812</td>
<td>3726</td>
</tr>
<tr>
<td>Mean</td>
<td>3821</td>
<td>3727</td>
</tr>
<tr>
<td>Coarse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-19</td>
<td>3639</td>
<td>3548</td>
</tr>
<tr>
<td>1-21</td>
<td>3648</td>
<td>3561</td>
</tr>
<tr>
<td>1-23</td>
<td>3520</td>
<td>3404</td>
</tr>
<tr>
<td>1-32</td>
<td>3759</td>
<td>3661</td>
</tr>
<tr>
<td>Mean</td>
<td>3642</td>
<td>3544</td>
</tr>
</tbody>
</table>

The propagation velocity of sound waves in the rock mass is closely related to the elasticity of the medium, the degree of hard density and the integrity. In general, fresh and complete rock has a relatively large longitudinal wave velocity. With an increase in the degree of weathering, the wave velocity is bound to decrease. The continuous decrease in wave velocity also reflects the fact that rock porosity increases as the number of freeze–thaw cycles increases.
3.3. Uniaxial Compressive Test

3.3.1. Damage Features

Under uniaxial compressive strength (UCS), various damage patterns were observed, mainly related to loading methods, loading rate, and the water content of specimens, etc. Basically, two patterns were encountered, namely, compressive shear failure and tensile fractures, as shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** Typical rock compressive damage morphotypes after different freeze–thaw cycles: (a) compressive shear failure; and (b) tensile fracture.

3.3.2. Uniaxial Compressive Strength Testing Results

Stress–strain curves are illustrated in Figure 2. It can be seen from Figure 2 that the stress–strain curves of sandstone conform to the general rule of rock deformation: they are divided into compaction stage-elastic, stage-shaping yield-failure, in which the compaction stage of the coarse sandstone is more obvious due to pores and fractures. The UCS of both rocks decreased with the increase of freeze–thaw cycles, and the corresponding strain increased at the peak intensity.

![Figure 2](image2.png)

**Figure 2.** Typical rock compressive damage morphotypes after different freeze–thaw cycles: (a) fine sandstone; and (b) coarse sandstone.

The concrete results of uniaxial compressive strength tests are listed in Table 4.
Table 4. Results of sandstone specimen uniaxial compressive strength tests.

<table>
<thead>
<tr>
<th>Sandstone Variety</th>
<th>Time of F–T Cycles</th>
<th>UCS (MPa)</th>
<th>Peak Value Strain (%)</th>
<th>Elastic Modulus (GPa)</th>
<th>Poisson Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>0</td>
<td>114.8</td>
<td>0.573</td>
<td>19.28</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>98.8</td>
<td>0.582</td>
<td>16.57</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>86.7</td>
<td>0.649</td>
<td>12.08</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>79.6</td>
<td>0.674</td>
<td>10.01</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>72.3</td>
<td>0.741</td>
<td>8.16</td>
<td>0.21</td>
</tr>
<tr>
<td>Coarse</td>
<td>0</td>
<td>104.1</td>
<td>0.672</td>
<td>18.2</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>90.1</td>
<td>0.68</td>
<td>15.1</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>83.9</td>
<td>0.786</td>
<td>11.3</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>74.2</td>
<td>0.813</td>
<td>8.2</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>64.4</td>
<td>0.862</td>
<td>6.9</td>
<td>0.28</td>
</tr>
</tbody>
</table>

3.4. Rock Integrity Decay Laws Based on Uniaxial Compressive Strength

3.4.1. Decay Index \( \lambda \) under the Different Times of Freeze–thaw Cycles

Taking the uniaxial compressive strength as rock integrity index, Equation (1) can be used to obtain decay index \( \lambda \):

\[
\lambda = \frac{1}{N} \ln \frac{I_0}{I_N} = \frac{1}{N} \ln \frac{UCS_0}{UCS_N}
\]  

where, \( UCS_0 \) is the uniaxial compressive strength before freeze–thaw cycling; \( UCS_N \) is the uniaxial compressive strength of the rock undergoing \( N \) freeze–thaw cycles.

The measurement of uniaxial compressive strength of fine and coarse sandstone after the different number of freeze–thaw cycles and \( \lambda \) obtained by Equation (3) are listed in Table 5.

Table 5. \( \lambda \) corresponding to the different freeze–thaw cycles.

<table>
<thead>
<tr>
<th>Sandstone Variety</th>
<th>Time of F–T Cycles</th>
<th>Real Measured UCS (MPa)</th>
<th>Decay Index ( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine</td>
<td>0</td>
<td>114.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>98.8</td>
<td>5.00 \times 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>86.7</td>
<td>4.68 \times 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>79.6</td>
<td>4.07 \times 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>72.3</td>
<td>3.85 \times 10^{-3}</td>
</tr>
<tr>
<td>Coarse</td>
<td>0</td>
<td>104.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>90.1</td>
<td>4.81 \times 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>83.9</td>
<td>3.60 \times 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>74.2</td>
<td>3.76 \times 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>64.4</td>
<td>4.00 \times 10^{-3}</td>
</tr>
</tbody>
</table>

It can be seen from Table 5 that with the increase in the number of freeze–thaw cycles, \( \lambda \) continues to change with a certain varying law. As far as the fine sandstone is concerned, \( \lambda \) continues to decrease, indicating that the integrity loss caused by the single freeze–thaw is rather serious in the initial freeze–thaw cycles; with the increase in the number of freeze–thaw cycles, the integrity loss caused by a single freeze–thaw gradually decreases and tends to become a certain constant. For the coarse sandstones, however, \( \lambda \) appears to decrease first and then increase with an increase in the times of freeze–thaw cycles. The following analysis focuses on fine sandstone.

Substituting the obtained \( \lambda \) for freeze–thaw cycles of \( N = 30, 60, 90 \) and \( UCS_0 = 114.8 \) MPa into Equation (1), we can obtain the corresponding decay equations in the following:

\[
UCS_N = 114.8e^{-0.008N}
\]  

\[
UCS_N = 114.8e^{-0.0047N}
\]
$$\text{UCS}_N = 114.8e^{-0.0041N}$$  \hfill (6)

The above decay development by Equations (4)–(6) and the measured uniaxial compressive strength are illustrated in Figure 3.

![Figure 3](image1.png)

**Figure 3.** Different \( \lambda \) corresponding to fine sandstone integrity decay curves and measured UCS.

It can be seen from Figure 3 that if Equation (2) is used to calculate \( \lambda \) of 30, 60 and 90 freeze–thaw cycles, then the equation and these 3 different \( \lambda \) values are used to calculate the uniaxial compressive strength after 120 cycles, UCS\(_{120}\), we obtain three different values of 63 MPa, 65 MPa and 70.5 MPa, respectively. The differences from the measured UCS\(_{120}\) are 9.3 MPa, 6.8 MPa and 1.8 MPa, respectively. A better prediction for rock integrity after a certain cycle number \( M \) can be made by \( \lambda \) obtained from another cycle \( N \) closer to \( M \). If the decay equation is characterized with the obtained \( \lambda \) in the 30 cycles, the obtained uniaxial compressive strength in the extrapolation \( N = 120 \) freeze–thaw cycles is 13% less than the measured value, i.e., the integrity loss after undergoing 120 freeze–thaw cycles is considerably overestimated.

Taking the uniaxial compressive strength of the marble [42] after different freeze–thaw cycles as an example, the results are illustrated in Figure 4.

![Figure 4](image2.png)

**Figure 4.** Different \( \lambda \) corresponding to marble integrity decay curves and measured UCS.
It can also be noticed from Figure 4 that better prediction for rock integrity after a certain cycle number \( M \) can be made by a \( \lambda \) obtained from another cycle \( N \) closer to \( M \). If the decay equation is characterized with the obtained \( \lambda \) in the 50 times of freeze–thaw cycles, the obtained uniaxial compressive strength in the extrapolation \( N = 150 \) times of freeze–thaw cycles is 45% less than the measured value, i.e., the integrity loss after undergoing 150 times freeze–thaw cycles is considerably overestimated.

The above analysis indicates that \( \lambda \) in the decay Equation (1) is not a constant but rather changes with the increase in the number of freeze–thaw cycles. When the rock integrity degree is characterized with the uniaxial compressive strength, \( \lambda \) (of fine sandstone and marble) decreases with the increase in number of freeze–thaw cycles, and gradually tend to be a constant. Therefore, when the obtained \( \lambda \) from a small number of freeze–thaw cycles is substituted into the decay equation, there will be a larger discrepancy between the calculated and measured results for the integrity after a larger number of cycles. The loss of the integrity is overestimated. The decay parameter that in previous studies is considered as a constant might only be reasonable for small number of freeze–thaw cycles.

What is worth noticing is that changes in the laws of \( \lambda \) with the number of freeze–thaw cycles vary with different rocks and, accordingly, micro-structures. In our testing program, for coarse sandstone, \( \lambda \) decreased first and then increased; while the \( \lambda \) of andesite [11] basically remains unchanged in the process of freeze–thaw cycles. The varying law can be different for different rocks, but it is also influenced by factors such as the structure components, grain shapes, pores and micro-cracks, etc.

3.4.2. Relationship of the Decay Parameter versus Porosity and Longitudinal Wave Velocity of the Sandstone

Taking UCS as the integrity index, it is necessary to perform freeze–thaw cycling and compression tests to obtain \( \lambda \); however, it is rather time- and labor-intensive and costly. It is therefore desirable to relate \( \lambda \) with some easily obtained indexes, so that the decay equation can be used to predict the UCS of rocks subjected to certain freeze–thaw cycles.

The fine sandstone \( \lambda \) decreases with the increase in the number of freeze–thaw cycles, which implies that greater integrity loss is caused by a single freeze–thaw cycle in the initial cycles; with the increase in number of freeze–thaw cycles, the integrity loss caused by a single cycle gradually decreases until it becomes a constant. At the same time, it can be seen from Tables 2 and 3 that, with the increase in freeze–thaw cycles, the porosity continues to increase and the longitudinal wave velocity decreases. This implies certain connections between these indexes.

The change of porosity and the change in the longitudinal wave velocity by a single freeze–thaw cycle are expressed as follows:

\[
\Delta n = n_N - n_0 \tag{7}
\]
\[
\Delta v = v_N - v_0 \tag{8}
\]

For convenience of application, the relationship between \( \Delta n \) and the decay index \( \lambda \) and that between \( \Delta v \) and \( \lambda \) are investigated and illustrated in Figures 5 and 6.

It can be seen from the above fitting that there is a good fit in the relationship between decay index \( \lambda \) and the porosity increment as well as in the velocity increment of the longitudinal wave (\( R^2 > 0.95 \)), in contrast, \( \lambda \) and \( \Delta v \) have a better-fitting relationship (\( R^2 > 0.98 \)).

\[
\lambda = -0.0011\Delta n + 0.0053 \quad R^2 = 0.956 \tag{9}
\]
\[
\lambda = 2 \times 10^{-6}\Delta v + 0.0051 \quad R^2 = 0.985 \tag{10}
\]

Substituting Equation (10) into the decay equation, respectively, using UCS to express the rock integrity, we obtain the following:

\[
\text{UCS}_N = \text{UCS}_0 e^{-(2 \times 10^{-6}\Delta v + 0.0051)N} \tag{11}
\]
As for fine sandstone, the simple and easily measured variation quantity of velocity of the longitudinal wave can be substituted into Equation (11), and the UCS after certain freeze–thaw cycles can be obtained.

4. Conclusions

In our paper, freeze–thaw cycle tests were carried out on coarse sandstones and fine sandstones collected from the side slopes of Muli coal mine in Qinghai Province under saturated conditions. Their physical and mechanical properties, after a number of freeze–thaw cycles, were investigated. Based on the decay equation suggested by Mutlutür [20] and taking UCS as the integrity index, the rock integrity decay laws were analyzed. The following conclusions were obtained:

1) The porosity of fine sandstone and coarse sandstone continues to increase with the increase in the number of freeze–thaw cycles, while the velocity of the longitudinal wave decreases with the increase in the number of freeze–thaw cycles.
waves of rocks of two kinds continues to decrease. Both indicate that the freeze–thaw functions can make the pores or micro-cracks in rocks continue to crack and expand.

(2) Based on the uniaxial compressive testing results of coarse sandstones and fine sandstones, and in combination with previous studies, the rock integrity decay laws were analyzed. The results indicate that the decay index $\lambda$ is not a constant value but changes with an increase in the number of freeze–thaw cycles. For the fine sandstone, $\lambda$ gradually decrease with the increase in freeze–thaw cycles and finally tends to become a certain constant ($\lambda = 0.00385$–0.005); with the coarse sandstones, $\lambda$ decreases at first and then increases ($\lambda = 0.00376$–0.00481);

(3) Taking UCS as the integrity index, for the fine sandstone, there is a good fitting relationship between decay index $\lambda$ and the porosity increment ($R^2 > 0.95$) as well as between the velocity increment of the longitudinal wave ($R^2 > 0.98$), $\lambda$ can, then, be deduced by the velocity increment of the longitudinal wave, and by further calculating the integrity indices (UCS) subject to the number of different freeze–thaw cycles.

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