Study on the variation of physical and mechanical characteristics under freeze-thaw condition

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Abstract: Subjected to freeze-thaw cycles, the deformation of physical and mechanical properties is the main cause of engineering disasters. Based on the analysis of the results of triaxial compression test after different freeze-thaw cycles, conclusions are drawn that: under the certain freeze-thaw cycles conditions, with the increase of confining pressure, the triaxial compressive strength, elastic modulus and the axial strain increase gradually, indicating that the failure of rock changes from brittle failure to plastic failure; in the case of same confining pressure, with the increase of the number of freeze-thaw cycles, the triaxial compressive strength, elastic modulus of rock decreases and the axial strain corresponding to peak stress gradually increase. With the increase of the number of freeze-thaw cycles, the cohesion of grit is in the form of exponentially decays to reduce, the internal friction angle changes very little.

1 introduction

In recent years, with the rapid development of China's coal resources in the Tibetan Plateau, the special large temperature difference freezing environment has become an important factor affecting the stability of open-pit slope. Subjected to freeze-thaw cycle, the deterioration of the physical and mechanical characteristics of rock is the main cause of the engineering disasters. scholars have done many researches on the deterioration of the physical and mechanical properties of the rock under the freeze-thaw environment, Xu Guangmiao^{[1][2][3]} obtained that with the increase of the number of freeze-thaw cycles, the uniaxial compressive strength of sandstone and shale decreased; Zhang Huimei^{[4][5][6]} had done the test at freezing and thawing temperature range of -20°C $\sim$ $+20^{\circ}\text{C}$ for 100 times, concluded that the tensile strength of the red sandstone and shale decreased with the increase of the number of freeze-thaw cycles; Su Wei^{[7][8]} carried out the uniaxial compressive and tensile test of the Tibetan granite porphyry copper after different freeze-thaw cycles, found that with the increase of the number of freeze-thaw cycles, the uniaxial compressive strength and the tensile strength both decreased, however, the amplitude of tensile strength is much larger than the uniaxial compressive strength. Xu Yujuan^{[9][10]} established a mathematical expression between uniaxial compressive strength and porosity of the rocks after different freeze-thaw cycles.

The strength and deformation of the rock under the freeze-thaw condition mostly obtained by the uniaxial compression test, however, the natural rock mass is in

the state of triaxial stress, the uniaxial strength and deformation is not sufficient to reflect the actual working conditions. therefore, the study on the rocks' strength and deformation characteristics after different freeze-thaw cycles under triaxial compression load have important theoretical and practical significance for open-pit slope stability analysis and freeze-thaw disaster prevention and control. In this paper, the strength and deformation of rock in triaxial stress state after different freeze-thaw cycles are studied by means of MTS815 Testing System, then analyze the variation of the strength and deformation under different freeze-thaw cycles an different confining pressure.

2 Test

2.1 Sample Preparation

The grit samples were obtained from the MuLi open-pit drilling for represents, then the rock samples were processed into standard compression specimens ($\Phi 50 \times 100\text{mm}$) through core drilling, cutting, grinding processes, which is in strict compliance with the requirements of International Society for rock mechanics test specification. After the preparation of the specimen, standard specimens were observed, screening as much as possible to reduce the effect of sample dispersion of test results. Finally, the number of the samples for the triaxial test is 20.

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Table 1 Original properties of grit

	Dry weight g/cm ³	Saturated weight g/cm ³	Saturated water content(%)	Porosity %
Mean Value	2.51	2.54	1.42	2.05

2.2 Test Program

(1) Freeze-thaw temperature range

According to the annual change of the temperature measured by Muli open-pit mine, the temperature changes is reflected in a typical year test period temperature changes by similar principles. This study considers the average minimum temperature in winter and the average maximum temperature in summer, freeze-thaw cycle is defined as a temperature range of -25°C~+25°C.

(2) Freeze-thaw cycles

With reference to the service year of mine, taking into account the effect of freeze-thaw cycles of the extent of the damage to the rock, the maximum number of freeze-thaw test is designed for 120 times.

(3) Freeze-thaw cycle time

Taking into account the test of rock lithology, the freeze-thaw cycle test of freezing time of 8h, the melting time of 8h, a freeze-thaw cycle is 16h.

(4) Value of the confining pressure

Considering the lower coal seam of 1 coal floor, using heavy liquid pressed formula $P = K \cdot \gamma \cdot H$, $K = 0.013$, the confining pressure value set in this experiment is 1MPa, 2MPa, 3MPa three levels.

3 The analysis of physical characteristics of grit under freeze-thaw condition

Due to the thermal expansion coefficient of the mineral composition of the grit, when the temperature decreases or increases during the freeze-thaw process, the contraction and expansion of the mineral is different, which will result in changes in the physical characteristics. This chapter analyze the variation of the quality, saturated water content, porosity and velocity under freeze-thaw condition, and the causes of the changes in the physical characteristics of grit.

Fig 1 Variation of velocity after different freeze-thaw cycles

Fig 2 Variation of porosity after different freeze-thaw cycles

Based on the analysis of the physical properties of saturated grit after different freeze-thaw cycles we can conclude that: with the increase of the number of freeze-thaw cycles, the velocity decreases, the porosity increases. The main reason is that the phase transition of 9% volume expansion, which leads to the crack propagation of rock, at the same time, due to the influence of the temperature gradient of the potential in the water freezing process, the moisture migration to the segregation of the ice, whereby causing segregation ice growing.

4 Analysis of triaxial compression tests under freeze-thaw condition

According to triaxial partial stress - strain curves of grit, we can get the maximum principal stress test results at different freeze-thaw cycles and different confining pressures.

Table 2 Triaxial compressive strength under different freeze-thaw cycles

Freeze-thaw cycles	σ_1 (MPa)		
	$\sigma_3 = 1 \text{ MPa}$	$\sigma_3 = 2 \text{ MPa}$	$\sigma_3 = 3 \text{ MPa}$
0	109.4	116.6	121.8
30	94.8	100.1	107.4
60	87.9	94.2	100.5
90	81.1	87.3	93.6
120	72.6	78.8	85.1

We can conclude: with the increase of the number of the freeze-thaw cycles, the triaxial compressive strength of grit decreases continuously.

4.1 The analysis of freeze-thaw cycles affecting on the strength of grit

In order to vividly see the freeze-thaw cycles affecting on the strength, we plot the scatter diagram between the triaxial compressive strength and freeze-thaw cycles under the same confining pressure conditions, then carry out data fitting.

$$\begin{aligned}\sigma_1 &= 0.001N^2 - 0.4081N + 108.38 & R^2 &= 0.96 \\ \sigma_1 &= 0.0012N^2 - 0.4375N + 115.22 & R^2 &= 0.97 \\ \sigma_1 &= 0.0009N^2 - 0.403N + 120.81 & R^2 &= 0.96\end{aligned}$$

Fig 3 The effect of freeze-thaw cycles on the triaxial compressive strength

As it can be seen from Fig 3, with the increase of the number of freeze-thaw cycles, the peak triaxial compressive strength decreases gradually. The main reason is the expansion of existing cracks, connections and generate new crack .and cause stiffness decreased coarse sandstone.

4.2 The analysis of the confining pressure affecting on the strength

Fig 4 The effect of confining pressure on the triaxial compressive strength

with the increase of confining pressure, the triaxial compressive strength of the grit increases. In order to vividly see the confining pressure affecting on the strength, we plot the scatter diagram between the triaxial compressive strength and the confining pressure under the same freeze-thaw cycles conditions.

4.3 The variation of the cohesion and internal friction angle under the freeze-thaw condition

we can conclude that the main form of the grit failure is shear failure. according to Mohr-Coulomb strength criterion, c , ϕ value are calculated under different freeze-thaw cycles:

Table 3 c , ϕ value under different freeze-thaw cycles

freeze-thaw cycle	Mohr -Coulomb strength criterion		Mohr circle		average value	
	C MPa	ϕ °	C MPa	ϕ °	C MPa	ϕ °
0	20.69	46.39	20.79	46.24	20.74	46.32
30	17.48	46.70	17.56	46.55	17.52	46.63
60	16.26	46.55	16.26	46.55	16.26	46.55
90	14.97	46.40	14.97	46.40	14.97	46.40
120	13.27	46.40	13.27	46.40	13.27	46.40

with the increase of the number of freeze-thaw cycles, the cohesion of the grit decreases from 20.74MPa to 13.27MPa, reducing 7.47MPa. the inter friction angle changes little. In order to vividly see the freeze-thaw cycles affecting on the cohesion, we plot the scatter

diagram between the cohesion and the freeze-thaw cycles, then data can be fitted to give:

$$C(N) = 20.74e^{-0.004N} \quad R^2 = 0.96$$

Where $C(N)$ is the cohesion of the grit, MPa; N is the freeze-thaw cycle.

4.4 The relationship between the triaxial compressive strength and freeze-thaw cycles, the confining pressure

According to the Mohr-coulomb strength criterion, we can come:

$$\sigma_1 = 2c \frac{\cos \phi}{1 - \sin \phi} + \frac{1 + \sin \phi}{1 - \sin \phi} \sigma_3$$

So the relationship between the triaxial compressive strength and the freeze-thaw cycles, the confining pressure is:

$$\sigma_1 = 100.809e^{-0.004N} + 6.246\sigma_3$$

5 Conclusion

(1) The analysis of physical indexes after different freeze-thaw cycles of saturated grit shows that: With the increase of the number of freeze-thaw cycles, the velocity decreases, the porosity increased. The main reason is that the phase transition of 9% volume expansion, which leads to the crack propagation of rock, at the same time, as freezing heave pressure is generated by the volume expansion, which caused the water migration inward.

(2) Based on the analysis of saturated grit triaxial compression test after different freeze-thaw cycles, conclusions are drawn that: The main form of fracture of grit are shear failure; under the certain freeze-thaw cycles conditions, with the increase of confining pressure, the triaxial compressive strength, elastic modulus and the axial strain increase gradually, indicating that the failure of rock changes from brittle failure to plastic failure; in the case of same confining pressure, with the increase of the number of freeze-thaw cycles, the triaxial compressive strength elastic modulus decreases, and the axial strain gradually increases.

(3) With the increase of freeze-thaw cycles, the cohesion of sand decreases exponentially, and the internal friction angle changes little, which indicates that freeze-thaw cycles have a greater impact on the bond strength, but a smaller impact on the rock friction strength. The main reason is that in the freeze-thaw process, the expansion of the phase transition between the mineral particles in tensile stress exceeds the crack propagation threshold, resulting in the bonding force between the rock particles decrease. The triaxial compressive strength is fitted with confining pressure, freeze-thaw cycles by Mohr-Coulomb theory. Compared with the test results, the rationality of the formula is verified.

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