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Geo-Ref Information Services-USA, List B of Scientific Journals, Poland, Directory of Research Journals

ISSN 0974-5904, Volume 09, No. 06

International Journal of Earth Sciences and Engineering

December2016,P.P.2753-2758

Experimental Research On The Dilatancy Of Rock Joints With Different Opening Values Under Freezing Conditions

HUOHUA LI[1], SHIWEI SHEN[1,2]* AND YAN XU[1]
[1]*College of Construction Engineering, Jilin University, Changchun Jilin 130026, China*
[2]*State Key Laboratory of Frozen Soil Engineering, Lanzhou Gansu 730000, China*
Email:*ssw2580@jlu.edu.cn*

Abstract: Direct shear tests were conducted on frozen rock joints. The variations in the dilatancy features of these joints were investigated under the correlativity of different opening values and the maximum fluctuation degrees of the joints. Furthermore, a contrastive analysis of the dilatancy features of rock joints at freezing and normal temperatures was conducted. Results showed the total regularity of the "initial dilatancy and subsequent compression." However, different dilatancy features were revealed under different normal stresses when the opening value of a joint was smaller than its maximum fluctuation degree. The dilatancy amount of the joint reach edits maximum value under a medium stress level, and the final normal displacement increased as the normal stress increased. By contrast, only a minimal dilatancy effect was induced in the growth stage of the shear stress because of the ice microcrystalline particle dislocation, which occurred when the opening value was greater than the maximum fluctuation degree of the joint. Under the same normal stress, when the joint opening value was large, the amount of dilatancy was relatively small compared with that when the joint opening value was small, and the final normal displacement of the joint surface was relatively great compared with that when the opening value was small. The contrastive analysis results on the dilatancy features of joints under normal temperature showed the following: at a normal temperature, the dilatancy amount of the joint monotonously increased with an increase in the shear displacement, and the final dilatancy amount was larger than that under freezing conditions.

Keywords: *Opening value of joint, Freezing, Shear test, Dilatancy, Contrastive analysis.*

1. Introduction

In line with Western Development Strategy and the strategy to rejuvenate northeast old industrial bases of China, more and more engineering construction projects are being developed in the permafrost regions. In tunnel and slope engineering, the strength of rock joints plays a decisive role in engineering stability. In a previous survey, frost damages were found to be induced numerous times in the joint development area in tunnels and mouths of the side slopes of caves in permafrost regions. The variations in the shear mechanical properties of frozen rock joints are the root causes of these damages. Given that the rock masses in the tunnels and slopes in permafrost regions are perennially in a frozen state, frozen rock joints are the most likely to be the weak parts in construction projects. Owing to the shear behavior of frozen rock joints, the dilatancy phenomenon can occur as a result of the ice rupturing; the joint surface induces a "climbing" effect given that the rock slide is accelerated along the ice crack. Thus, research on the dilatancy of rock joints under freezing conditions is of great significance in solving the stability problems of tunnels and mouths of the slide slopes of caves in permafrost regions.

Numerous scholars in China and abroad have studied the shear strength and dilatancy of rock joints and related fields [1-4], as well as the surface properties of these joints in freezing and thawing soil. Barton conducted a large number of direct shear tests on rock joints and proposed a JRC–JCS peak shear strength formula, which is suitable for low normal stress conditions [5,6].Li Kai-hui conducted a microscopic study of the shear process of rock joints [7,8].Li Hai-bo evaluated the relationship between shear strength and shear rate and that between rolling angle and normal stress by investigating concrete samples [9]. Zhao Yan-lin conducted numerical experiments on the shear properties of rock joints with random morphology and determined the relationships of joint roughness with the peak shear strength and dilatancy angle; they also established a nonlinear dilatancy constitutive model for rock joints [10]. Wang Bin applied the theory of plastic mechanics to the Jinping marble damage control during the entire process of triaxial loading and unloading test and consequently established a nonlinear model for dilatancy angle by simultaneously considering the effects of confining pressure and plastic parameters [11]. Using Barton's shear strength formula and the multifractal features of a rock mass structural plane as basis, Chen Shi-jiang proposed a method for determining shear strength [12].

Li Zhen established a mechanical model for the hardening–softening and dilatancy features of chlorite schist by conducting a triaxial compression test under

different confining pressures and considering the influence of the stress state for plastic evolution [13].Barton presented a dilatancy numerical model by comparing test data; consequently, the Barton dilatancy model was established [14].

In this study, the research object comprises the rock joints in the Jiangluling tunnel in Gonghe–Yushu Road along the Qinghai G214 line. First, the joint morphology was obtained by 3D scanning. Then, reserve shear tests were performed on joints with different openings. After the filling water freezes, the dilatancy features of the frozen joints were analyzed under different stress levels.

2. Joint specimen preparation and test method:

2.1Test equipment

Shear tests were conducted using a CSS-342 rock mass shear tester in the Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University. The machine consists of four major components, including main engine, hydraulic system, servo control system, and computer control and processing system.

The surface morphology of the rock joint was obtained with a TJXW–3D portable rock surface profile meter, which adopts stereo vision method, structured light method, and binocular imaging in measuring the rock surface. The initial morphological scanning results of the joint surface are shown in Figure 1; joint surface height probability distribution is shown in Figure 2.

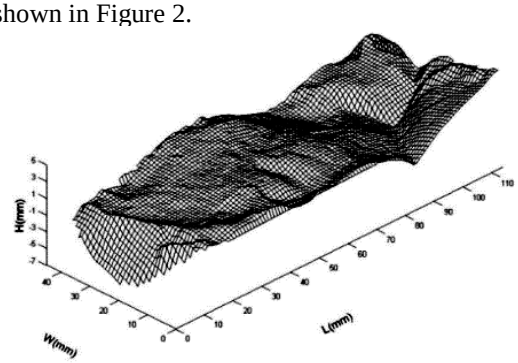


Figure 1: *Diagram of initial surface*

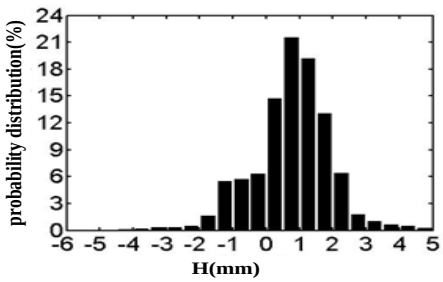


Figure 2: *Probability distribution of joint height topography of rock joint*

2.2 Specimen preparation

In this study, natural rock joint surfaces in permafrost regions were selected and placed in a shear box with dimensions of 300 mm× 150 mm× 150 mm (length × width × height). The label material selected for the model was composed of 32.5R cement, sand, and water mixed at water: cement: sand ratio of 1:2:3.

The models were poured into the mold. After pouring, the mixture was cured under the condition of standard curing for 28 d, after which the joint plane was frozen. The top and bottom joint surfaces were placed in a waterproof box, and a certain space between the two surfaces was reserved. In addition to the scope of joint, all gaps were filled with high-density EPS foam board, and then water was injected into the box. After the box was filled with water, the entire box was placed in a low-temperature control thermostat machine for freezing at a temperature of −35°C for 12 h. The freezing diagram and images of the frozen joint surface specimens are shown in Figure 3 and Figure 4, respectively. After freezing was accomplished, the area of the joint surface (along the joint plane transverse and longitudinal directions; the maximum distance from a point to the boundary of the rectangle) was filled with ice.

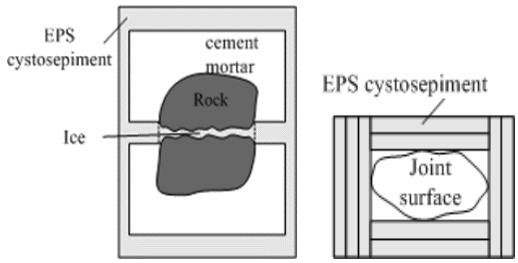


Figure 3: *Diagram of frozen rock joint*

Figure 4: *Photo of frozen rock joint*

2.3 Test method and process

Figure 2 shows that the elevations of the joint surfaces are distributed between 4 and 5 mm (height fluctuation degree of 9 mm). The frozen joint openings (i.e., the reserve width between two frozen joint surfaces) are set to 6 and 12 mm to highlight the relationship between the joint fluctuation degree and the dilatancy features. Direct shear tests were conducted on the frozen rock joints under different normal stresses on the CSS-342 rock mass shear tester. The design normal stresses were 0.39, 0.63, 0.89, and 1.14 MPa. The normal stress was applied according to the load control method adopting

increments of 2 kN/min. Then, according to the deformation control method adopting increments of 2 mm/min, the shear loading is applied, according to the same rate of loading. The parameters for the tests are shown in Table 1.

Table 1: *Testing program on the shear strength of frozen rock joint*

Test number	Normal stress(MPa)	Opening (mm)
1	0.39	6
2	0.63	6
3	0.89	6
4	1.14	6
5	0.63	12
6	0.89	12
7	1.14	12

The experiments were conducted to investigate the relationship of the surface opening of a joint with its fluctuation degree, as well as the effect of this relationship on shear mechanical behavior. During experiments, opening values of 6 mm (less than the 9mm fluctuation degree of the joint plane) and 12 mm (greater than the 9mm fluctuation degree of the joint plane) were adopted for the reserve shear tests. The first shear tests were conducted with the 12mm opening followed by the 6mm opening to avoid the destruction of the joint surface under the condition of repeated shear caused by the changes in the fluctuation degree. With the same opening, normal stress was applied from low to high.

3. Analysis of test results:

3.1 Dilatancy features of frozen rock joints with 6 mm opening under different normal stresses

After freezing the rock joint surface with a 6mm opening, the shear tests were conducted under different normal stresses of0.39, 0.63, 0.89, and 1.14 MPa. The relationship curves between shear displacement and normal displacement are shown in Figure 5.

During shearing, the shear plane displacement moving down is positive. Therefore, the "rising" phase of the curve represents the dilatancy trend of the joint surface. When the shear displacement of the joint surface reaches 3–5 mm, the ice is broken. As shown in Figure 5, under the effect of normal stress at all levels, the dilatancy phenomenon occurs on the joint surface during shearing. Furthermore, the relationship curves of shear displacement and normal displacement can be divided into three stages. The first stage is the shear stress increasing stage. Under different normal stresses, before the ice is broken, the shear behavior of the joint surface demonstrates different degrees of dilatancy. In the process of shearing, microcrystalline particles of the ice along the direction of the shear stress mainly ruptured (similar to dense sand dilatancy phenomenon), as shown in region A of Figure 5. The second stage is the ice breaking stage. During the test, when the shear displacement is more than 5 mm, the ice is broken. After this point, the relationship curves between shear displacement and normal displacement were significantly different. Under a low normal stress, the normal stress restrain effect on the joint surface is not significant; thus, the normal displacement fluctuation is not sizeable. Under a medium normal stress (0.63 and 0.89 MPa), the ice exhibits an obvious dilatancy phenomenon. This result is mainly ascribed to the opening of the joint being less than its maximum fluctuation degree; as a result, the "climbing" effect of the rock joint occurs, and the normal displacement rebound is significant. Under a high stress level (1.14 MPa), the normal displacement shows a slow growth trend. This result is mainly due to the "climbing" effect; the ice is crushed under the high normal stress, as shown in region B of Figure 5. The third stage is the after shearing stage. After the shear displacement exceeds 15 mm, the normal displacement leveled off and showed an obvious compression feature under other normal stresses, in addition to0.39 MPa. This result is mainly attributed to the action "after the compression" process under the maximum normal stress after the joint surface moves along the direction of the shear through the highest point, as shown in region C of Figure 5.

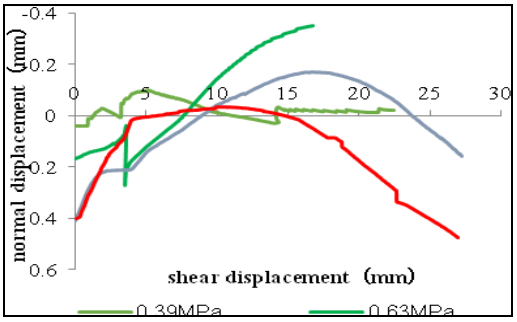


Figure 5: *Relationship curves between shear displacement and normal displacement under different normal stresses on the frozen joint with 6mm opening*

However, Figure 5 also clearly shows that the changes in the amplitude of the normal displacement with respect to the horizontal displacement are obviously different under the different normal stresses. Before the shear stress is applied, the normal displacement of the ice (the initial normal displacement in Figure 5) increases with an increase in the normal stress. In the entire shear process, the normal displacement of the ice demonstrates a total regularity of "initial dilatancy and subsequent compression." However, the dilatancy amounts between the highest point and the initial normal displacement of the curve are significantly different. The normal stress level is greater, whereas the low and high stress levels are smaller. In addition, after the shear test, the normal displacement of the ice eventually increases with increasing normal stress.

3.2 Dilatancy features of frozen rock joints with 12 mm opening under different normal stresses

After freezing the rock joint surface with 12 mm opening, the shear tests were conducted under

different normal stresses of0.63, 0.89, and 1.14 MPa. The relationship curves between shear displacement and normal displacement are shown in Figure 6.

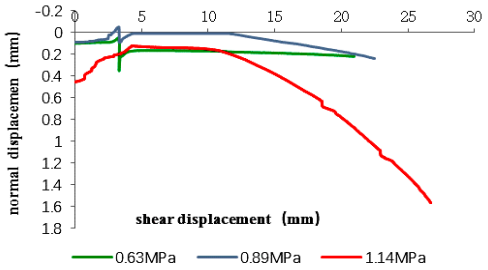
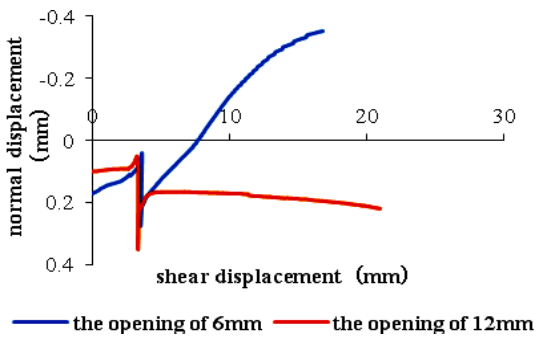


Figure 6: *Relationship curves between shear displacement and normal displacement under different normal stresses on the frozen joint with 12mm opening*

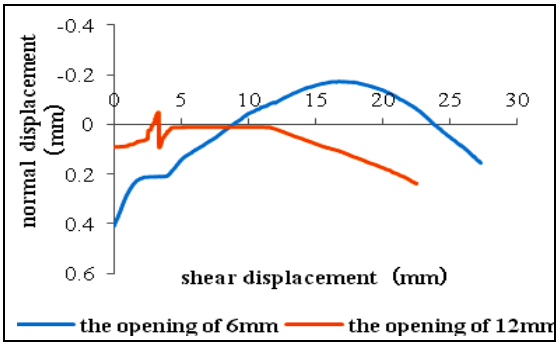
As shown in Figure 6, when the joint opening is 12 mm (ice thickness is greater than the maximum fluctuation degree of the joint surface), in addition to the shear stress increasing stage (shear displacement within 3–5 mm), a minimal dilatancy effect occurs because of the faulting among microcrystalline particles of the ice; the other phase, in which shear displacement is greater than 5 mm, does not exhibit a dilatancy phenomenon. Given that the ice thickness is greater than the maximum fluctuation degree, a "climbing effect" is no longer induced. After shear failure, the ice continues to be compressed under the normal stress. The trend of the normal displacement increasing with increasing normal stress is revealed.

3.3Dilatancy features of the frozen rock joints with different openings under the same normal stress

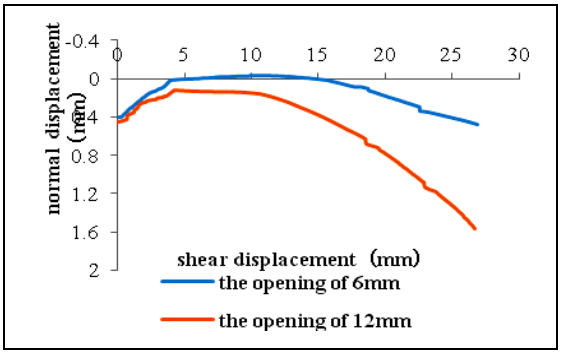
Additional tests were conducted to further clarify the effect of rock joint opening (ice thickness) on the dilatancy features. The samples had openings of 6 mm and 12 mm, and direct shear tests were conducted under normal stresses of 0.63, 0.89, and1.14MPa. Under different normal stress, the relationship curves between shear displacement and normal displacement were analyzed, and the analysis results are shown in Figure 7.



(a) Normal stress(0.63 MPa)



(b) Normal stress (0.89MPa)



(c) Normal stress (1.14MPa)

Figure 7: *Comparison of shear test results for different opening values under same normal stress*

As shown in Figure 7, under different normal stresses, the dilatancy features of the frozen joints with different openings show a similar trend: the dilatancy amounts of the large joint opening (12 mm) are less than those of the small opening (6 mm) under each normal stress value. After the end of the shear process, the normal displacement of the joint surface becomes eventually greater than that of the small opening. This result is mainly because a "climbing" effect is not induced during the shear process when the joint plane opening is greater than the maximum fluctuation degree. At this point, the joint surface deformation is caused mainly by the normal stress.

In the chemistry field, water molecules are connected by Van der Waals' force and hydrogen bond under the normal temperature condition. When the water freezes, ice crystal molecules present a box arrangement form, and obviously increase the hydrogen bond number, which lead to the prominent structural strength. To freeze joint, the ice crystal structure will be compressed under normal stress. During the shearing process, friction forces are formed between solid ice crystal and the arrangement mode is changed when it is broken, which leads to the dilatancy phenomena.

4. Contrastive analysis of the dilatancy features of joint planesat freezing and normal temperatures:

Numerous studies have studied the dilatancy features of rock joint surfaces at room temperature by tests or simulations [15–17]. Given that joint surface roughness and normal stress are similar concepts, the

direct shear test data obtained by Tang Zhi-cheng under different normal stresses were analyzed14. The test results under normal stressesof 0.63, 0.89, and 1.14 MPa for an opening of 6 mm were used to generatethe relationship curves between dilatancy amountand shear displacement and were compared with the results undernormal stressesof 0.5, 1.0, and 1.5 MPa reported in a previous study. The relationship curves are shown in Figure 8.

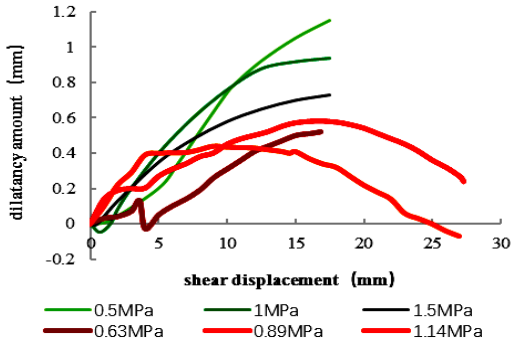


Figure 8: *Comparison of curves of joint dilatancy amountat freezing and normal temperatures*

As shown in Figure 8, at room temperature, the dilatancy amount increases gradually over time during the shear test. The dilatancy amounts of the frozen rock joints demonstrate the "initial increase and subsequent decrease" trend. During the shear test at room temperature, the joint surface is always in a state of compaction under the effect of normal stress. Thus, the "climbing" effect is significant, demonstrating an opposite relationship between the direction of normal displacement and stress, and the dilatancy amount increases gradually. After the ice in the frozen rock joint breaks, a large normal stress is difficult to bear because the intensity of the ice is lower. At the same time, the cracked ice has compressed density in the process of "climbing." After the shear displacement reaches a certain degree, the ice is broken completely, and then the joint surface has compressed density under the normal stress. Therefore, the total regularity of "initial dilatancy and subsequent recovery" is revealed.

The trend of dilatancy under the different normal stresses at the same temperature is evident. The dilatancy amount declines significantly with increasing normal stress. In general, the dilatancy amount of the joint surfaces at room temperature is larger than that of frozen rock joints.

5. Conclusions:

The following conclusions have been drawn from the investigation on the dilatancy features of the frozen rock joints with different openings and under different normal stresses:

(1) When the opening of a join is less than its maximum fluctuation degree, microcrystalline particles of the ice ruptures, inducing different amounts of dilatancy under the shear stress. After the ice is broken, the convex parts of the rock joint surface induces "climbing" effect, and the dilatancy phenomenon is very evident at the same time. After the shear displacement exceeds 15 mm, compression occurs on the joint surface under a normal stress. In summary,the total regularity of "initial dilatancy and subsequent compression" is revealed.

(2) When the opening of the joint is smaller than its maximum fluctuation degree, the dilatancy amount shows that the secondary normal stress level is greater, whereas the high and low stress levels are smaller. The normal displacement of the ice eventually increases with an increase in the normal stress.

(3) When the opening of the joint is greater than its maximum fluctuation degree, the microcrystalline particles of the ice ruptures, inducing slightly different dilatancy amounts during the initial phase of the shear test. After the ice is broken, given the absence of a "climbing" effect, the ice is compressed, and the normal displacement increases with increasing normal stress.

(4) At a normal temperature, the dilatancy amount appears to increase monotonically. Under freezing conditions, given that the ice layer encounters difficulty in bearinga considerable normal stress, the shear stress is affected by the normal stress at the same time. Therefore, the trend of the dilatancy amount is considered "initial increase and subsequent decrease". In general, the dilatancy amount of the frozen rock joint surfaces is smaller than that of rock joints at room temperature.

6. Acknowledgements:

This work was supported by the Project of National Science and Technology Support Program (No. 2014BAG05B05); National Natural Science Foundation of China (No. 41502270); Science and Technology Development Project of Jilin Province, China (No. 20150520076JH); Open Fund of State Key Laboratory of Frozen Soil Engineering (No. SKLFSE201506).

References

[1] Y. P. Qin, K. Song, L. W. Liu, J. S. Wu, H. T. Song. Dimensionless Analysis of the Temperature Field of Surrounding Rock in Coalface with a Finite Volume Method. International Journal of Heat and Technology. Volume 33, Issue 3., pp.151-157, 2015.

[2] X. H. Huang, C. M. Wang, T. Z. Wang, Z. M. Zhang. Quantification of Geological Strength Index Based on Discontinuity Volume Density of Rock Masses. International Journal of Heat and Technology. Volume 33, Issue 4., pp.255-261, 2015.

[3] W. T. Liao, H. Q. Zhu, Y. Yang, et al. Study on Low Temperature Mechanical Properties of

Rocks under High Strain Rate. Revista de la Facultad de Ingeniería, Vol. 31, Issue 5., pp. 197-208, 2016.

[4] F. Song, H.B. Chai, L.Q. Ma and H.B. Hu, "Numerical Analysis on Deformation Behavior of Geosynthetic-Reinforced Slopes", Revista de la Facultad de Ingeniería, Volume 31, Issue 3., pp. 40-48, 2016.

[5] N. Barton. Rock Mechanics Review-The Shear Strength of Rock and Rock Joints. International Journal of Rock Mechanics and Mining Science & Geo-mechanics, Volume 13, Issue 9., pp.255-279, 1976.

[6] N. Barton, V. Choubey, The Shear Strength of Rock Joints in Theory and Practice. Rock Mechanics, Volume 10, Issue 1., pp.1-54, 1977.

[7] K. H. Li, P. Cao, K. Zhang. Macro and Meso Characteristics Evolution on Shear Behavior of Rock Joints. Journal of Central South University, Volume 22, Issue 8., pp.3087-3096, 2015.

[8] J. A. Wang, Y. X. Wang, Q. J. Cao, et a1. Behavior of Microcontacts in Rock Joints under Direct Shear Creep Loading. International Journal of Rock Mechanics & Mining Sciences, Volume 7, Issue 2., pp.217-229, 2015.

[9] H. B. Li, H. P. Feng, B. Liu. Study on Strength Behaviors of Rock Joints under Different Shearing Deformation Velocities. Chinese Journal ofRock Mechanics and Engineering, Volume 25, Issue 12., pp.2435-2440, 2006.

[10] Y. L. Zhago, W. Wan, W. J .Wang, et a1. Shear Numerical Simulation of Random Morphology Rock Joint and Nonlinear Shear Dilatancy Model. Chinese Journal of Rock Mechanics and Engineering, Volume 32, Issue 8., pp.1666-1676, 2013.

[11] B. Wang, J. B. Zhu, A. Q. Wu, et al. Experimental Study of Nonlinear Dilatancy Characteristics Based on the Damage-Controlled Method. Rock and Soil Mechanics, Volume 36, Issue 4., pp.981-987, 2015.

[12] S. J. Chen, W. C. Zhu, Q. L. Yu, et al. Shear Strength Research on Rock Joint Surfaces Based on Multifractal Theory. Rock and Soil Mechanics, Volume 36, Issue 3., pp.703-711, 2015.

[13] Z. Li, H. Zhou, Y. Z. Song, et al. Mechanical Model of Chlorite Schist Considering Hardening-Softening and Dilatancy Characteristics. Rock and Soil Mechanics, Volume 34, Issue 2., pp.404-410, 2013.

[14] N. Barton. Review of a New Shear Strength Criterion for Rock Joints. Engineering Geology, Volume 7 Issue 4., pp.287-332,1973.

[15] Z. C. Tang, C. C. Xia, Y. L. Song, et a1. Analysis of Peak Dilation Strength and Model of Peak Dilation Angle for Artificial Joint. Chinese Journal of Rock Mechanics and Engineering, Volume 31, Issue 5., pp.3038-3044, 2012.

[16] C. Zhang, X. B. Mao, H. M. Ni, et a1. Study of Numerical Simulation of Rock Dilatancy. Journal of Xi'AnUniversity of Science and Technology, Volume 31, Issue 3., pp.181-187, 2011.

[17] W. G. Xiao, G. S. Dui, T. L. Chen, et a1. A study of Constitutive Model Coupling Dilatancy and Degradation for Jointed Rock. Chinese Journal of Rock Mechanics and Engineering, Volume 28, Issue 12, pp.2535-2543, 2009.