Experimental Investigation on Shear Strength of Grout Infilled Fractures with Different Thickness

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Abstract. Grouting has been widely used in practice rock engineering to enhance the stability and strength of fractured rocks mass, as well as to decrease the permeability of fractured rocks. The crack width of joints in nature varies, and grouting engineering may endure different stress conditions during the construction and operation life of tunnels and underground spaces in fractured rock mass. In order to study the strength and deformation characteristics of grouting joints with different thickness under different stress conditions, the shear test of grouted rock samples is carried out. The red sandstone with similar JRC which was obtained by splitting test was selected as the test rock mass. Three kinds of grouting thicknesses are considered, and the mechanical performance of grouting rocks under different normal forces is analyzed. When the normal stress is low, adopting pure cement slurry can greatly improve the shear mechanical properties of rock mass, the biggest increase of cement mortar and pure cement slurry is 1.51 times. However, when the normal stress is high, grouting materials will weaken the peak stress of rock mass. For different grouting thickness, the shear strength of grouting rock mass decreases with increasing thickness. But the mechanical properties of grouting rock mass changed a little as the grouting thickness is over 4mm. Comparing the final failure mode, it can be seen that sliding is dominant with normal stress 0.5MPa, then the failure mode turns to split & sliding, cut off & sliding respectively with increasing normal stress.

1. Introduction

Grouting is a very effective method to reduce the permeability of fractured rock mass and to enhance the stability of slope, tunnels and underground engineering (Zhang 2014). During the construction and operation life of different slope engineering in fractured rock mass, engineering or naturally caused changes in shear stresses may influence the mechanical response of grout infilled fractures, which can induce lager deformation or stress concentration. This is one of the main reasons that trigger disasters in slopes, tunnels, or many other underground engineering.

Considering the importance of practical rock engineering, many previous studies focused on the shear strength of unfilled rock (Patton. 1966, Barton and Choubey. 1977, Grasselli. 2003, Xia et al. 2014). Patton et al. firstly introduced the undulation angle into the Mohr-Coulumb criterion to establish the double linear shear strength criterion accounting for the impact of dip angel and normal stress in the 1960s. Barton and Choubey (1977) adopted the joint roughness coefficient (JRC) to describe joint roughness, and the JRC of individual joints can be described by 10 standard JRC profiles. Moreover,
the widely used JRC-JCS peak shear strength criterion were established with simple form. Grasselli. (2003) found the distribution of the damage area was closely related to shear direction, joint roughness, joint strength and normal stress. The steepest area facing the shear direction had a crucial effect on the peak shear strength. Then, he established a 3D peak shear strength model. Xia et al. (2014) modified the 3D peak shear strength model with more explicit physical meaning.

A large number of studies focus on the mechanical properties of unfilled joints, which provide reference for the research of grouted joints. Goodman (1970) found the peak shear strength of filled joints was between that of filled materials and that of unfilled joints. Papaliangas et al. (1993) researched the impact of filling degree on shear strength. The peak shear strength of infilled joint decreases with the increase of filling thickness, but the peak shear strength becomes stable with filling thickness 1.25 - 1.5. Indraratna et al. (2008) studied the mechanical properties of clay filled rock using regular serrated rock-like materials. When the filling ratio exceeds a certain value, the filling strength is no longer controlled by the thickness. On the contrary, the shear strength decreases with the increase of the thickness. Lu et al. (2016) studied the filling ratio of regular sandstone joints. the shear stress and stiffness values decrease with increase in the filling ratio between 0.1 and 1.0. Tian et al. (2018) proposed a peak joint strength model of rock filled with cement slurry considering the three-dimensional morphology of joint surface, filling degree and the ratio of rock wall strength to cement stone strength. Although the mechanics of rock fractures infilled with infilled materials (e.g., fault gouge, cement mortar) has been studied in the past, the experimental studies on the shear properties of grout infilled splitting rock sample is rare. So the research of the split sandstone rock samples infilled with different thickness is necessary.

The main objective of this experimental study is to investigate the changes in the stress of sandstone fractures infilled with grout during the shear process under a constant normal stress. The rock fracture always vary in many kinds of patterns, which leads to the different forms of grouting distribution(Figure.1). Therefore, a clear understanding of the shear process of grout infilled fractures with different stress is critical. In this study, we considered three kinds of grouting thicknesses with rough surfaces, the shear strength of which was tested using a CSS 1950 rock rheological testing system.

![Figure 1. Photos of grout infilled fractures](image1)

![Figure 2. Photos of splitting equipment](image2)

2. Method

2.1. Sample preparation

To study the influence of infilled grout of rock fractures, it is important to avoid the effect of the matrix failure as much as possible. Red sandstone from Hunan, China, was selected in this study with the uniaxial stress 40MPa. Ordinary Portland cement (OPC), grade P.O. 42.5, with an average density of 1744 kg/m³.

Infilled fractures with rough surfaces are considered in this experiment, and unfilled fracture samples with rough surfaces are also included as the reference. Rough fractures were generated by axially splitting the red sandstone blocks along the middle planes (Figure.2). Grout with water-to-cement ratio of 0.5 was selected to provide high workability during grouting and ensure the fracture infilling...
strength. To prepare “sandwich” samples including grout with a designed width, glass box with two rulers of 20 mm placed on the both lateral sides of the fractured rocks. Fix one side of the sample, and adjust the other side of the sample according to the rulers, the designed infilling thickness 2mm, 4mm, 8mm were obtained (Figure. 3). The grouted fracture samples were then cured in the environment at a temperature of 20 ± 2 °C and relative humidity of 95% for 28 days. The samples were numbered as “unfilled”, and “T2 , T4 and T8”, “N0.5, N1, and N2,”, where “T” and “N” represent pure cement slurry and normal stress. For example, T4N1 represents the infilled thickness is 4mm and normal stress is 1MPa. The uniaxial stress, internal friction, adhesion stress of pure cement slurry  is 23.5MPa, 62°,0.97MPa respectively.

![Figure 3. Process of making infilled sample](image)

2.2. Experiment procedure

In this study, the following test procedure was designed. Before test fracture samples were scanned by rock surface topography instrument (Figure. 4). The TJXW-3D optical scan can project a raster strip image of visible light onto the sample’s surface. The sample is pho-tographed, and three-dimensional imaging process software is used to accurately compute the spatial coordinates (X, Y and Z) of each point on the sample’s surface using the Delaunay triangle method. Excluding some samples with large deviations, 12 samples with similar apparent dip angle are selected to carry out experiment. The average apparent dip angle is between 11.8° and 14.5°, and the roughness coefficient calculated by fitting method is close to a constant.

The test samples were divided into two groups. In the first group, the upper and lower samples were combined into an unfilled rock sample. In the other group, the upper and lower samples were grouted into a completed sample with grouting materials. The direct shear test was carried out by using the Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji university CSS 1950 rock mechanics test system (Figure. 5). In order to record the normal deformation and stress in the loading process, the normal loading rate is set at 0.1 kN/s. As the normal force is loaded and stabilized, the shear force is loaded. The shear loading is controlled by displacement, and the shear rate is 0.5mm/min. In the whole shear process, the failure process of rock sample is recorded by camera, and the final failure pattern of the infilled sample is also recorded, which provides the basis for the shear failure of split rock after grouting.
3. Results

3.1 Mechanical behavior

The shear deformation of unfilled joints with different normal stress is showed in Figure 6 (a). On the whole, with the increase of normal stress, the shear stress increases correspondingly. When the normal stress is less than 1MPa, the shear stress is composed of two parts: (1) shear stress increases rapidly with growing shear displacement. (2) the shear stress keeps to a constant value. When the normal stress is 2MPa, the shear stress is composed of three parts: (1) the SA segment, (2) the AB segment; (3) BC segment. With increasing shear displacement, line SA shows a rapid increase in shear stress. Peak shear stress is reached when shear displacement is close to 1 mm. Line AB represents a sudden decrease in shear stress with continue increasing shear displacement. In segment BC, shear stress keeps nearly constant.

In Figure 6 (b), the shear strength of T2N0.5 has a rapid increase as the shear displacement is less than 1mm. Segment AB shows a gradual decrease in shear stress, and segment BC shows undulation in shear stress with increased displacement. Segment CD has similar evolution with segment AB, and segment DE remains nearly constant. The shear strength of T4N0.5 and T8N0.5 have similar evolution with that of unfilled joints under 2MPa, but the decrease stage is more rapidly. In general, the average displacement corresponding to the peak stress is 1mm, and the average value of infilled samples is close to that of unfilled sample in the sliding segment.

In Figure 6 (c), the change rules of infilled samples with different thickness show similar tendency which are composed of 3 segments, but there is a slowly increase stage in the star stage of T4N1. The average displacement corresponding to the peak stress is 1.1mm, and the average value of infilled samples is a little bit bigger than that of unfilled sample in the sliding segment.

In Figure 6 (d), the change laws of infilled samples with different thickness show similar tendency with that of unfilled sample, but the infilled samples have longer downward section (segment AB and BC). The degree of deviation of the three kinds of thickness in sliding segment is less than that in low normal stress. The average displacement corresponding to the peak stress is 1.3mm, and the average value of infilled samples is less than that of unfilled sample both in the peak stress point and in the sliding segment.
When the normal stress is low (0.5MPa and 1MPa), infilled grout can improve the peak shear stress by a large margin. The average peak stress enhances 135.8%, 84.7% respectively as the normal stress is
0.5 MPa and 1 MPa in Figure 7. However, the average peak stress decreases 7.8% with normal stress 2 MPa. The difference of peak stress with different infilled thickness is minor as the normal stress is equal. In detail, the peak stress of 2 mm infilled thickness is highest and that of 8 mm is lowest. That is to say, the peak shear stress decreases with the increasing infilled thickness.

### 3.2 Failure mode

The shear process was recorded by digital camera, and the ultimate failure mode of infilled specimens under different normal stress can be obtained in Figure 8.

![Figure 8. Typical ultimate failure mode of infilled samples with different thickness](image)

When the joint filling thickness is changed, various failure modes are observed. Figure 8 shows surface images of typical failed rock samples with various infilled thickness. Figure 8 (a), (b) and (c)
show sliding failure mode, Figure. 8 (d), (e) and (f) show split and sliding failure mode, Figure. 8 (g), (h) and (i) show cut off and sliding failure mode.

4. Conclusions
In this experiment, we studied the shear strength of three kinds of infilled thickness under different normal stress, some conclusions are drawn below.
1) With the grout thickness increasing, the shear strength of the infilled joints decreases, while the shear strength difference of three kinds of thickness is minor.
2) When the normal stress is low, adopting grout can improve the shear strength of rock samples by a large margin. But grouting will decrease the shear strength of rock joints to some degree with high normal stress.
3) The failure modes of infilled samples change with the normal stress level. The failure mode of infilled samples show sliding, split & sliding, cut off & sliding respectively, when the normal stress is in low level, medium level, and high level.

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