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Investigation of meso-failure behaviors of Jinping marble using SEM with bending loading system

Jianping Zuo [a,b,*], Xu Wei [a,b], Jianliang Pei [c], Xiaoping Zhao [c]

[a] School of Mechanics and Architectural Engineering, China University of Mining and Technology, Beijing 100083, China
[b] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Beijing 100083, China
[c] College of Water Resources and Hydropower, Sichuan University, Chengdu, Sichuan 610065, China

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ABSTRACT

In this study, the meso-failure mechanism and fracture surface of Jinping marble were investigated by means of scanning electron microscope (SEM) with bending loading system and laser-scanner equipment. The Yantang and Baishan marbles specimens from Jinping II hydropower station were used. Test results show that the fracture toughness and mechanical behaviors of Yantang marble were basically higher than those of Baishan marble. This is mainly due to the fact that Baishan marble contains a large percentage of dolomite and minor mica. Crack propagation path and fracture morphology indicated that the direction of tensile stress has a significant effect on the mechanical behaviors and fracture toughness of Baishan marble. For Yantang and Baishan marbles, a large number of microcracks around the main crack tip were observed when the direction of tensile stress was parallel to the bedding plane. Conversely, few microcracks occurred when the direction of tensile stress was perpendicular to the bedding plane. The presence of a large number of microcracks at the main crack tip decreased the global fracture toughness of marble. The results of three-point bending tests showed that the average bearing capacity of intact marble is 3.4 times the notched marble, but the ductility property of the defective marble after peak load is better than that of the intact marble. Hence, large deformation may be generated before failure of intact marbles at Jinping II hydropower station. The fractal dimension of fracture surface was also calculated by the cube covering method. Observational result showed that the largest fractal dimension of Yantang marble is captured when the direction of tensile stress is parallel to the bedding plane. However, the fractal dimension of fracture surface of Yantang and Baishan marbles with tensile stress vertical to the bedding plane is relatively small. The fractal dimension can also be used to characterize the roughness of fracture surface of rock materials.

1. Introduction

Jingping II hydropower station is located on the Jinping Bay of Yalong River in the junction of three cities including Muli, Yanyuan and Mianning. There are four diversion tunnels in Jinping II hydropower station with an average length of about 16.67 km and the diameter of lining tunnel of about 11.8 m. Also, there are two parallel auxiliary traffic tunnels (tunnels A and B), about 60 m away from the diversion tunnel connecting Jinping I and II stations (CHIDI, 2003; HEC, 2005). In terms of site-specific geological conditions, many geological hazards, such as high geostress, water inrush, rockburst and unstable surrounding rocks, are frequently reported in the construction process of the traffic tunnels, which not only delay construction schedule, but also threaten the lives of workers (Wu et al., 2005; Zhang and Fu, 2008).

Since the earlier 1950s, researchers have been focusing on the deformation and failure mechanisms of rocks. Using high rigid testing machine and true triaxial test, more physico-mechanical properties of rocks have been understood (Paterson and Wong, 2005; Mogi, 2006; Jaeger et al., 2007). In the earlier 1970s, many studies were conducted on the mechanical properties of rocks under unloading stress paths (Swanson and Brown, 1971; Crouch, 1972). In the last three decades, studies on deep underground rocks have been developed increasingly with the major projects in high geostress regions, such as the Three Gorges project and Jinping hydropower station (Li and Wang, 1993; Wu, 1997; Zhou, 2000; You, 2002; Pei et al., 2009). However, for Jinping marbles, the results of conventional triaxial tests vary widely. Thus, the deformation and failure mechanisms and strength of rocks under unloading stress paths still remain unclear, which are challenging issues in deep underground

* Corresponding author. Tel: +86 10 62331358.
E-mail address: zjp@cumtb.edu.cn (J. Zuo).

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engineering in China. In addition, Ha et al. (1998) and Li (1999) have developed the theory of unloading rock mechanics concerning the deformation and failure of rocks.

For deep rocks in Jinping hydropower station, Wang et al. (2008) conducted 4 tests on marble specimend in the diversion tunnels of Jinping II hydropower station under different stress paths, including uniaxial loading and unloading, triaxial compression, pre-peak and post-peak unloading confining pressure under high stress conditions. Wu et al. (2010) showed slabbing failure of marble at Jinping II hydropower station with true triaxial blasting experiments on coarse marble and aplite marble. Yan and Xia (2008) carried out rheological tests on Jinping marble under multilevel unloading confining pressures, and proposed that unloading confining pressure affects the instantaneous deformation and the rheological deformation of rocks. Huang and Huang (2010) analyzed the fracture surface of specimens under triaxial unloading and scanning electron microscope (SEM), and presented the regulations of deformation, failure and strength of marble at Jinping I hydropower station under different unloading rates in high stress environments.

However, most of the above-mentioned studies focused on macro-failure of Jinping marble and few studies are on meso-scale. The scale of meso-failure is between those of macro- and micro-failure. In this paper, rock failure at meso-scale was discussed, namely at about millimeter and centimeter scales. As is known, the failure of rock is a multi-scale mechanical process, which is very complex and irreversible. If the information of crack initiation, propagation and fracturing by means of in-situ observation can be obtained, it is helpful for understanding rockburst occurring in deep rocks of Jinping project. In this study, the meso-failure mechanisms of marble with preset flaws and intact marble were investigated. With the help of SEM, a series of three-point bending tests on Yantang and Baishan marbles was also conducted.

2. Rock specimens and experimental procedure

The rock specimens were sampled from Jinping traffic tunnels A (stake No. AK12 + 621 at Yantang) and B (stake No. BK12 + 28.7 at Baishan), at the depth of 2010 m from surface. The two parallel tunnels have a center-to-center distance of about 35 m, and cross-sectional area of 5.5 m × 5.7 m (width × height) and 6.0 m × 6.3 m, respectively. The depth of the tunnels is basically 1500–2000 m, accounting for about 73% of total length. The maximum overburden depth is about 2375 m. The rocks in the area where the tunnel passed through consisted of marble, limestone, sandstone and other hard rocks. Geostress of the project increases with depth, and the major principal stress is 42.11 MPa. Slight or moderate rockburst occurred in the tunnels PD1 and PD2 at Dashuigou when the excavation depth was up to 2000 m. Rockburst occurred occasionally at the auxiliary tunnel. With increasing excavation depth, more serious rockburst accidents may occur. Yantang marble in tunnel A is mainly laminar containing 54.7% calcite and 45.3% dolomite associated with marked bedding features. Baishan marble in tunnel B contains 91% dolomite, 8.6% calcite and only 0.4% mica. Since Baishan marble is relatively homogeneous, it is regarded as an isotropic material.

The bending loading system is used in this study. The size of three-point bending marble specimen was 10 mm × 5 mm × 20 mm, as shown in Fig. 1. The experiments were conducted using the SEM with loading system in the State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (CUMT) (Zuo et al., 2007, 2009, 2010). Using the SEM with loading system, crack propagation path can be continuously recorded to reveal the meso-failure mechanism of Jinping marble. In the test, displacement loading mode was adopted, which was set to be 10^{-4} mm/s.

According to the site-specific conditions, intact and layered rocks were tested respectively to evaluate the stability of the auxiliary traffic tunnel. According to standard three-point bending test and mechanical behaviors of Jinping marble, the specimens were divided into three groups, i.e., two Yantang groups (groups A1 and A2) and one Baishan group (group B). The two Yantang groups consist of group A1 with bedding plane parallel to tensile stress direction and group A2 with bedding plane perpendicular to tensile stress direction. Fig. 2 shows test specimens prepared for testing.

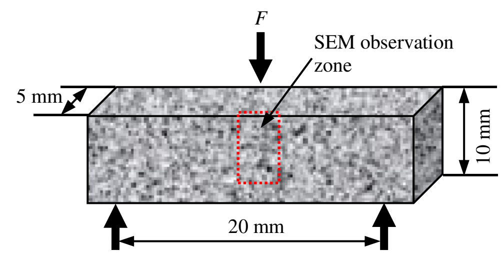

Fig. 1. Rock specimen size and loading condition.

3. Tests on the meso-failure of Jinping marbles

3.1. Meso-failure characteristics of intact Jinping marble

In order to obtain meso-failure characteristics of intact Jinping marble, the three-point bending tests were conducted on marble specimens of Yantang and Baishan groups. Fig. 3 shows the relations between the bending stress and deflection of specimens of the three groups. In Fig. 3a and b, it is observed that brittle fracturing at failure occurs in the two groups of Yantang marbles. The deformation of all the specimens is linearly distributed with applied load before peak, and almost no plastic deformation occurs. Brittle failure suddenly occurs in rock specimens when the peak load is reached. Since the direction of tensile stress induced by bending is perpendicular to the bedding plane, Jinping marble specimens of group A2 are more easily to fracture than those of group A1. Experimental results show that the peak load of specimens of group A1 is 1.7 times that of group A2. As shown in Fig. 3c, ductile failure of Jinping marbles of Baishan formation is observed when the peak load is reached, and no disintegration is observed. It can also be noted that the residual strengths exist after the peak load. The peak load of Baishan marble is basically lower than the strength of Yantang marble (group A2), about 10%–30%.

According to the principle of bending theory, the deflection δ is assumed to be linear with the imposed load P:

$$\delta = \frac{Pl^3}{48EI} \quad (1)$$

where E is the elastic modulus of rock specimen, l is the effective span (20 mm), and I is the area moment of inertia of the cross-section.

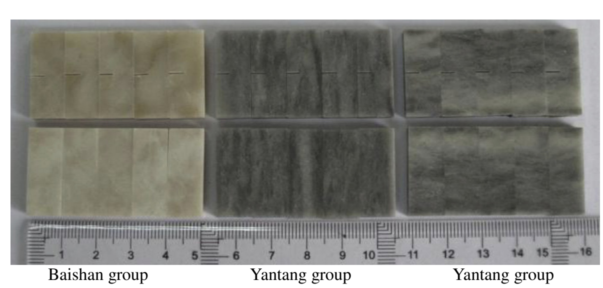

Fig. 2. Three-point bending specimens of Jinping marble.