International Journal of Mining Science and Technology 22 (2012) 213–221

Contents lists available at SciVerse ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Deformability characteristics of jointed rock masses under uniaxial compression

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ARTICLE INFO

Article history:
Received 12 June 2011
Received in revised form 17 July 2011
Accepted 26 August 2011
Available online 14 April 2012

Keywords:
Rock mass
Joint inclination angle
Joint connectivity
Uniaxial compression test
Axial stress-strain curve

ABSTRACT

We investigated the combined influence of joint inclination angle and joint continuity factor on deformation behavior of jointed rock mass for gypsum specimens with a set of non-persistent open flaws in uniaxial compression. Complete axial stress-strain curves were classified into four types, i.e., single peak, softening after multi-peak yield platform, hardening after multi-peak yield platform and multi-peak during softening. Observation of crack evolution on the specimen surface reveals that the deformation behavior is correlated to the closure of pre-existing joint, development of fractures in rock matrix and teeth shearing of the shear plane. To investigate the brittleness of the specimens, the ratio of the residual strength to the maximum peak strength as well as the first and last peak strains were studied. At the same joint inclination angle, the ratios between residual strength and the maximum peak strength and the last peak strains increased while the first peak strain decreased with the increase of joint continuity factor. At the same joint continuity factor, the curves of the three brittleness parameters vs. joint inclination angle can either be concave or convex single-peak or wave-shaped.

1. Introduction

In China, with the excavation depth increase of underground coal mine, the geological environment conditions becomes complex. Catastrophic events are very severe, such as large deformation, high strata pressure, frequent rock burst, gas accumulation and high temperature, which are great threats to safe and efficient exploration of deep-seated mineral resources. At great depth, due to high breaking of rock masses and high in situ stresses, deformations of the surrounding rock such as roof subsidence, floor heave and sidewall shrinkage could extremely be large and happens very often. Therefore, in shallow mining, support measurements in deep mining are aimed at maintaining the integrity and controlling the displacement of the surrounding rock as small as possible [1].

Understanding the deformation and failure mechanisms of rock mass plays a vital role on stability evaluation of rock structures and their support design. The mechanical response of rock mass depends on three factors: (a) the mechanical properties of the joints; (b) the mechanical properties of the intact rock; and (c) the geometry of the joint system.

The mechanical properties of the intact rock can be represented through the complete axial stress-strain curves in uniaxial or triaxial compression. Generally, the axial stress-strain curve of the intact rock is characterized by strain softening. As the confining pressure increases, the ductility of the rock increases, and the strain softening stage disappear gradually. Furthermore, the size, shape, loading conditions, temperature, time-dependent effects, and moisture content also affect the deformation behavior of the rock [2]. According to Bieniawski and Brace et al. the deformation behavior curve of a rock can conceptually be divided into six regions: (1) slight inclination region (toe) due to closure of microcracks, (2) liner elastic deformation portion in which the matrix deforms and the material has an intact rock behavior, (3) inelastic deformation portion in which the curve lose its linearity and fracture begin propagating in a stable manner, (4) strain-hardening stage in which fracture propagates in an unstable way until up to attaining peak strength, (5) early post-failure stage, in which the rock is still intact even though the internal structure is highly disrupted, and (6) late post-failure stage, in which the rock is parted to form a series of block and a constant fall of the residual strength [3,4].

As far as the mechanical behavior of the discontinuity is concerned, Barton-Bandis et al. proposed a model that incorporated the effect of roughness, wall strength, aperture, filling and seepage, which is popularly used and developed by many researchers [5].

However, the study on influence of the geometry of the joint system on mechanical behavior of rock masses is a rather more difficult task than those of the previous two factors, due to the presence of complicated discontinuity patterns, its inherent anisotropic nature, and highly nonlinear effect.

The properties of a jointed rock mass can be experimentally studied through field tests or laboratory physical model test. Field tests would provide the most useful information about the behavior of real rock masses. However, it is very difficult to obtain

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2095-2686/$ - see front matter © 2012 Published by Elsevier B.V. on behalf of China University of Mining & Technology.
doi:10.1016/j.ijmst.2011.08.012

sufficient data in most cases, and it is practically impossible to obtain large number of data necessary to establish valid relations with the above mentioned three factors. Compared with field test, laboratory physical model test is an attractive method, because it can systematically and evidently study the effect of every geometrical parameters, such as number of joint sets and their orientations, spacing, persistence, density and arrangement pattern. Therefore, it is useful to investigate the physical mechanism of the strength, deformability and failure process for jointed rock masses to obtain idealized analytical model.

In general, physical model test can be further divided into two categories: (1) tests with assemblages of blocks, and (2) tests with truly non-persistent joints.

Model tests of rock mass with assemblages of blocks can produce a combination of persistent and non-persistent joint sets, or entirely persistent joint sets. For example, Einstein and Hirschfeld carried out a series triaxial compression tests for gypsum models without joint and with continuous joints, including single joint, single set of joints and two orthogonal joint sets, and investigated the influences of confining stress, joint orientation, space and number of joint sets, on strength, deformation and failure modes [6]. They concluded that: there are two limits of Mohr envelope for rock mass strength, where the upper limit is for the failure through intact material, and the lower limit is for the sliding along a single smooth joint. The two limiting envelopes define three characteristic zones, i.e., a brittle zone, a ductile zone and a transition zone. Tiwari and Rao studied the post failure behavior of rock mass containing three continuous joint sets under triaxial and true triaxial compression [7]. The results show that strain hardening, softening and plastic behaviors depend on joint geometry and stress state. The joint dilation and sliding of a single joint plane caused strength reduction and deformability increase of the jointed rock mass. Wang et al. investigated the deformation of coal seams below stops by a plane strain model test with layered strata of the Hongling Mine in Shenyang as prototype [8]. They concluded that rock mass under goafs has upward movement after the protective seam being mined which caused floor heave.

Model tests with truly non-persistent joints can be achieved by inserting thin metallic sheets into a mold before setting the model materials. The mechanism of failure and deformation for rock mass with non-persistent joints is more complex than that with continuous joints, due to the stress concentration and crack propagation in the rock bridge. Numerous experimental investigations have been done on crack initiation, propagation and coalescence in rock or model materials with pre-existing open or closed flaws under different loading conditions. Various pre-existing open or closed flaws under different loading conditions, such as Lajtai, Gehle and Kutter, and Bai et al. under direct shear loading; Bobet and Einstein, Shen et al., Wong et al. and Tang et al. in uniaxial compression; Lin et al. and Prudencio and Jan in biaxial compression; and Liu et al. in a triaxial roadway model test, among many others, have been studied [9–18]. Gehle and Kutter classified the shear process of discontinuous jointed rock mass into three stages: tensile rupturing, rolling and sliding friction of dilatants joint zones, and sliding within the joint filling composed of brecciated material [10]. Moreover, they found that the shear stress-shear displacement curves had multiple peaks, and the largest shear resistance developed not just before rupture but also in one of the two subsequent phase of shearing as well. In the roadway model test, Liu et al. analyzed the deformation of the surrounding rock and the mechanisms of crack propagation on the production, growth and size of the broken rock zone [18].

The studies mentioned above have increased our knowledge about the effect of joint geometry on the behavior of jointed rock masses. However, in these researches, the geometry of the joints is specific, and very little direct experimental data were available for the dependence of the strength, deformability and fracture process of rock masses on the variation of the large range and combination of several geometrical parameters of a joint set.

In order to systematically study the influence of the two most important geometrical parameters, i.e., joint inclination angle, joint continuity factor and mechanical behavior of jointed rock masses, we performed a series of uniaxial compression tests on specimens with regular multiple parallel pre-existing open flaw arrangements. The influences of these two geometrical parameters on the strength and Young's modulus of the specimens were investigated in reference [19]. It was shown that with the increase of joint persistence, the strength decreased and deformation increased, and their relations are dependent on the joint orientation. In this paper, the complete axial stress-axial strain curves are further investigated, a classification is given and several ductility indexes are used to quantitatively study the dependence of the deformability of the simulated discontinuous rock mass specimens on the two geometrical parameters of the joint set.

2. Testing material and equipment

2.1. Specimen geometries

The specimens used in uniaxial test were plates with dimensions 150 mm high, 150 mm wide and 50 mm thick. A single set of parallel non-persistent open flaws penetrating through the thickness was arranged regularly, with identical spacing b and center distance h, fixed at 5 mm, see Fig. 1. The joint continuity factor k is defined as the ratio of joint area to the total area on the joint plane. In the tests, k was taken as 0.2, 0.4, 0.6 and 0.8, with joints width L_j of 0.6, 1.2, 1.8 and 2.4 cm, and is represented by characters B, C, D and E, respectively. The joint inclination angle β is defined as the angle of joint plane inclined to the horizontal. It varied from 0° to 90° with an increment of 15°, i.e., 0°, 15°, 30°, 45°, 60°, 75° and 90°, and is represented by 0, 1, 3, 4, 6, 7 and 9, respectively. For comparison, intact specimens were also included and are represented by character A. Therefore, totally 29 series of joint geometries were tested. For each series of joint geometries, at least three samples were made to observe repeatable experimental results. The series are described in the form of "joint continuity factor code followed directly by joint inclination angle code-number of the specimen in the series". For example, "E4-1" corresponds to the first specimen in series E4 with joint continuity factor $k = 0.8$ and inclination angle $\beta = 45°$.

2.2. Specimen preparation and materials properties

Specimens were made of a mixture of gypsum and water at a ratio of gypsum/water = 1:0.6 (wt/wt). The pre-existing open joints

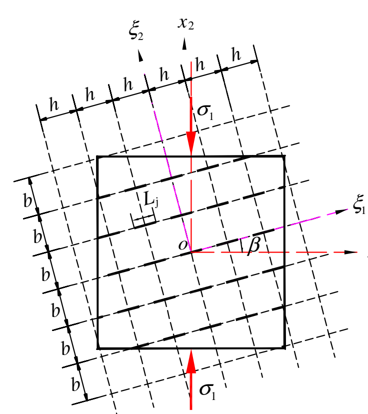

Fig. 1. Joint arrangement and geometrical parameters of the specimens.