www.czasopisma.pan.pl PAN www.journals.pan.pl

DE GRUYTER OPEN

Arch. Min. Sci., Vol. 60 (2015), No 4, p. 985–996

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.1515/amsc-2015-0065

XIANGYU WANG*

EXPERIMENTAL STUDY ON THE EFFECT OF MICRO-CRACKS ON BRAZILIAN TENSILE STRENGTH

EKSPERYMENTALNE BADANIE WPŁYWU MIKROSPĘKAŃ NA WYNIKI BADAŃ WYTRZYMAŁOŚCI NA ROZCIĄGANIE WEDŁUG METODY BRAZYLIJSKIEJ

For coal mine ground control issues, it is necessary to propose a failure criteria accounting for the transversely isotropic behaviors of rocks. Hence, it is very helpful to provide experimental data for the validation of the failure criteria. In this paper, the method for preparing transversely isotropic specimens and the scheme of the Brazilian tensile strength test are presented. Results obtained from Brazilian split tests under dry and water-saturated conditions reflect the effect of the development direction β of the structural plane, such as the bedding fissure, on the tensile strength, ultimate displacement, failure mode, and the whole splitting process. The results show that the tensile strength decreases linearly with increasing β. The softening coefficient of the tensile strength shows a sinusoidal function. The values of the slope and inflection point for the curve vary at the different stages of the Brazilian test. The failure mode of the rock specimen presented in this paper generally coincides with the standard Brazilian splitting failure mode. Based on the test results, the major influencing factors for the Brazilian splitting strength are analyzed and a mathematical model for solving the Brazilian splitting strength is proposed. The findings in this paper would greatly benefit the coal mine ground control studies when the surrounding rocks of interest show severe transversely isotropic behaviors.

Keywords: Brazilian split test; Dry and water saturation; Bedding fissure; Strength coefficient; Coal mine ground control

W związku z zagadnieniami ochrony powierzchni w kopalniach węgla, konieczne jest opracowanie odpowiednich kryteriów klasyfikacji uszkodzeń skał uwzględniających ich poprzeczną izotropowość. Pomocnym jest także dostarczenie danych eksperymentalnych niezbędnych do walidacji kryteriów uszkodzeń. W pracy tej zaproponowano metodę przygotowywania próbek wykazujących izotropowość poprzeczną, omówiono także sposób przeprowadzania testu na rozciąganie metodą brazylijską. Wyniki testu uzyskane na sucho oraz w warunkach nasycenia próbki wodą wskazują wpływ kierunku rozwoju β płaszczyzny

* SCHOOL OF MINES, KEY LABORATORY OF DEEP COAL RESOURCE MINING, MINISTRY OF EDUCATION OF CHINA, CHINA UNIVERSITY OF MINING & TECHNOLOGY, 1 UNIVERSITY AVENUE, XUZHOU 221116, CHINA. E-mail: wangxiangyu79@126.com

strukturalnej (np. płaszczyzn spękań) na wytrzymałość próbki na rozciąganie, maksymalne przemieszczenia, rodzaj uszkodzenia oraz przebieg procesu pękania. Wyniki testu wskazują, że wytrzymałość na rozciąganie maleje liniowo wraz ze wzrostem wartości β. Współczynnik mięknienia próbki w trakcie próby wytrzymałościowej na rozciąganie ma przebieg krzywej sinusoidalnej. Wartości kąta nachylenia oraz punkt przegięcia krzywej różnią się dla poszczególnych etapów próby wytrzymałościowej. Tryb uszkodzeń próbek skalnych przedstawiony w artykule zasadniczo pozostaje w zgodzie z typowymi odkształceniami rejestrowanymi w trakcie testu metodą brazylijską. W oparciu o wyniki eksperymentu, przeanalizowano główne czynniki wpływające na wytrzymałość próbek na rozciąganie i zaproponowano odpowiedni model matematyczny do obliczania wytrzymałości. Wyniki przedstawione w artykule stanowią poważny przyczynek do badań stabilności gruntu i ochrony powierzchni w rejonach górniczych w przypadku gdy sąsiadujące z kopalnią skały wykazują izotropowość poprzeczną.

Słowa kluczowe: badania na rozciąganie metodą brazylijską, próbki suche i nasycone wodą, płaszczyzny spękań, współczynnik wytrzymałości, ochrona powierzchni w kopalniach węgla

Introduction

Initially, all failure criteria in rock mechanics are borrowed from those developed for continuous materials that are homogeneous and isotrpoic. They are most suitable for man-made materials for which those criteria have been developed. Consequently, a fairly accurate prediction on the strength and failure mode can be commonly captured when evaluating the failure behavior of man-made materials. In coal mine ground control, however, the strata surrounding the mining operations are seldom homogeneous and isotropic. Therefore, the application of those failure criteria for ground control operations is very complicated and often met with prediction failure (Peng, 2007; Peng, 2008; Li et al., 2015). This is believed to be one of the main reasons that cause the discrepancy between the model predicted and in-mine observation or instrumentation results in most of the case studies handling the issues of coal mine ground control by using numerical modeling (Morsy & Peng, 2002; Suchowerska et al., 2013; Li et al., 2014). To address the dilemma, many researchers have developed plenty of failure criteria that can be implemented in the numerical modeling packages to simulate the transversely isotropic behavior of rocks (Hoek & Brown, 1980; Kulatilake et al., 1995; Tien & Kuo, 2001).

Most of the proposed failure criteria for transversely isotropic rocks generally provide fairly accurate simulation of the experimental data in the respect of the state of stress at failure and the failure mode. However, the validation of the proposed failure criteria, in most cases, is mainly focused on the camparison between the model predicted and experimental results obtained from uniaxial and/or triaxial compressive tests. Ideally, a failure criterion should also be able to predict the stress-strain relationship of the rock specimens under tensile conditions. Hence, it is necessary to provide additional experimental data for the validation of the failure criteria for the transversely isotropic rocks under tensile conditions.

The tensile strength and tensile properties will vary with changes in the external conditions such as temperature, confining pressure, humidity, and structural plane (Cai & Kaiser, 2004; Coviello et al., 2005). The Brazilian split test is a conventional method for determining tensile strength. During the test, the tensile failure process caused by compression from the radial disk is influenced by various interior and external factors, including the content of water and the structural plane of the tested specimen.

A number of researchers have carried out studies on the effect of anisotropic properties on the Brazilian tensile strength (Khanlari et al. 2014a & 2014b; Tan et al. 2014). Based on the assessment of the influence of strength anisotropy on the measured peak strength for four different types of rock samples in the Brazilian test, Dan et al. (2013) deemed that: 1) the degree of anisotropy has a strong influence on the measured peak strength; 2) the orientation of the sample in relation to the loading direction is not important for nearly-isotropic materials; and 3) strongly anisotropic materials show a strong dependence of the peak strength on the sample orientation relative to the loading direction. Erarslan & Williams (2012) pointed out that there is substantially higher tensile stress concentration at the center of a disk with a pre-existing crack than in a disk without a pre-existing crack.

Water is another important factor affecting the Brazilian tensile strength (Li et al., 2012; Yilmaz, 2010). The tensile strength of a sample dropped to nearly half of its dry value after it was soaked in water for one week, and decreased further only slightly after the specimen was immersed in water for three weeks or ten weeks. Wong & Jong (2014) used a high-speed video system to show that the cracking processes of dry and wet specimens are distinctly different in terms of the speed of crack propagation and the number of cracks that developed. The softening coefficient of Brazilian tensile strength is higher than and linear relative to that of uniaxial compressive strength, and the splitting strengths are nearly the same for dry and saturated rings with an internal diameter of 20 mm (Yilmaz, 2010).

While the studies mentioned above analyzed the influence of a single factor on the Brazilian tensile strength, here we investigate the Brazilian tensile properties under the effect of two external factors (dry and water-saturated conditions) and one internal factor (fracture direction). The influences of different fracture directions on the strength softening coefficient and Brazilian splitting properties are obtained. Based on our results, a mathematical model for solving the Brazilian splitting strength is proposed. It would greatly benefit the coal mine ground control studies when the surrounding rocks of interest show severe transversely isotropic behaviors.

Description of the problem

The selection of shale specimens for the Brazilian split test should comply with the provisions of the International Society for Rock Mechanics (ISRM, 1978). The specimen should be discoid with a diameter of 50 mm, and the ratio of thickness to diameter should be 0.2-0.75. The thickness in this test is 25 mm. The rock specimen was obtained by the drilling method. To get the different angles between the load plane and fracture angle, the drilling direction was changed to obtain fracture angles (β) of 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The drill cores were cut into discoid shapes and then polished to meet the requirements of the standard Brazilian split test, as shown in Fig. 1. The shale specimens were divided into two groups for each fracture angle with 10 specimens in each group. One group was stored dry at a room temperature, while the other was soaked in water. After 120 hours, the moisture content of the water-saturated specimen was 2.1%. A MTS-793 servo testing machine was used to conduct the tests.

Methodology

The test scheme is shown as Fig. 2. The rock specimens were divided into two groups: one under dry conditions and the other in water-saturated conditions. In each group, the rock specimens were subdivided into eight sub-groups according to the different fracture angles (β), with five shale specimens in each sub-group. A total of eighty (2 × 8 × 5) specimens were loaded for testing. The test apparatus was an MTS-793 servo testing machine. Each specimen was loaded at a constant rate (200 N/s) until reaching its failure point. The test data was recorded every 0.04 s. The test result of a standard Brazilian split test with $\beta = 37°$ was used to verify the accuracy of the test results.

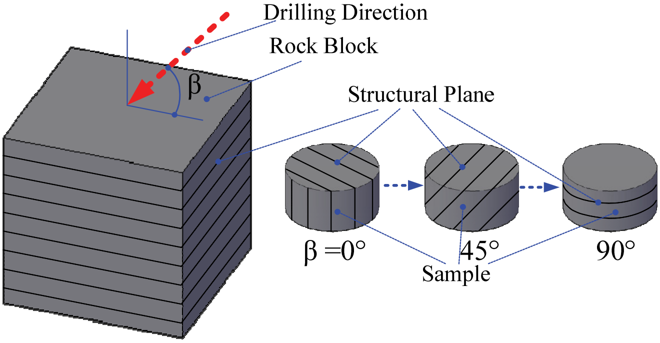


Fig. 1. Brazilian split test sample preparation method Self-Elaboration

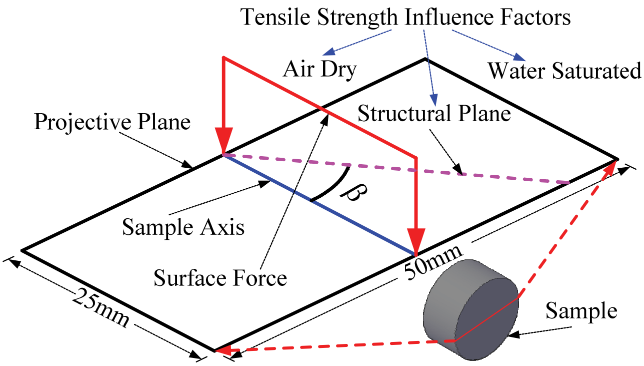
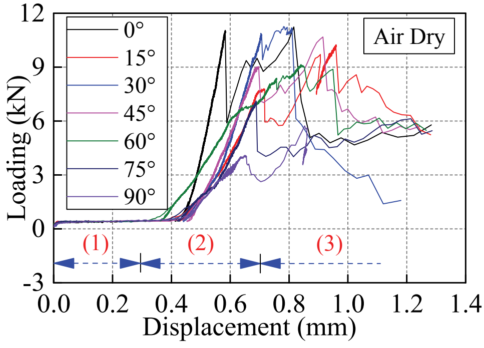


Fig. 2. Brazilian split test and its three influencing factors Self-Elaboration

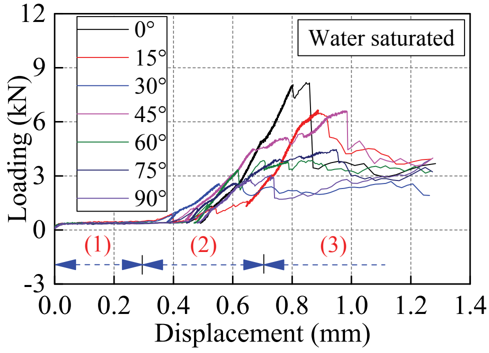
Results

(a) Brazilian test process

In a conventional Brazilian split test (Su et al., 2013), the curve of the load VS displacement can be divided into three stages: the compaction stage (stage 1), the elastic stage (stage 2), and the yielding failure stage (stage 3). As shown in Fig. 3, the mechanical properties in each stage of the Brazilian split test show distinct values because of the effect of the different fracture directions and water conditions.



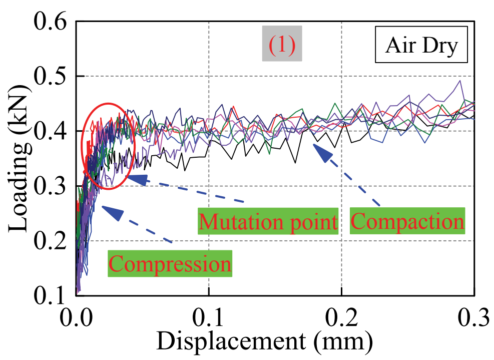
(a) Air dry condition



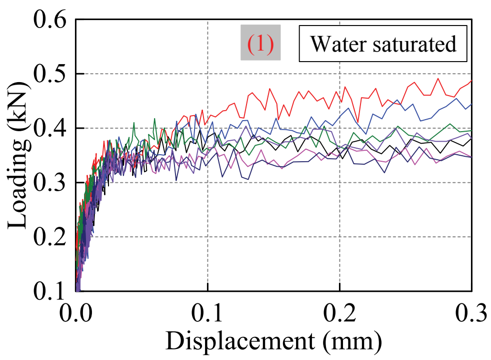
(b) Water saturated condition

Fig. 3. Load versus displacement for various fracture angles Self-Elaboration

In the compaction stage in Figs. 4a and 4b, partial compaction and long-term creep appear. The inflection point in the compaction process occurred at a load of approximately 0.3-0.4 kN. The slope of the curve remains almost constant throughout the loading process. The creep value under the water-saturated condition, reaching 0.35-0.45 mm, was larger than that under the dry condition (0.3-0.4 mm).



(a) Air dry condition

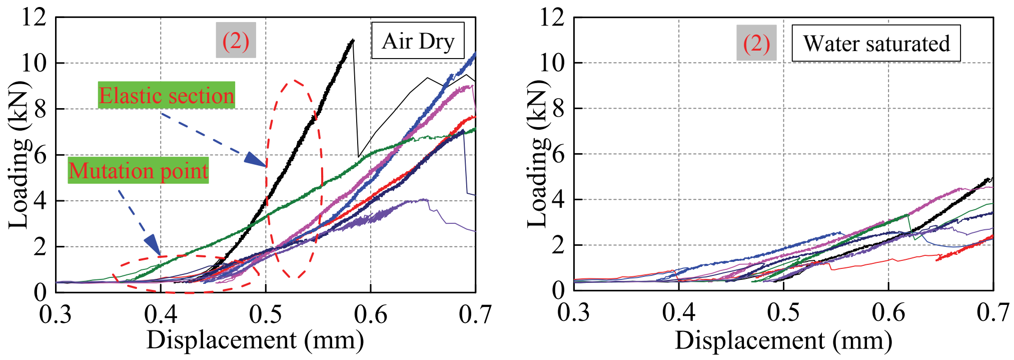


(b) Water saturated condition

Fig. 4. Load versus displacement in the compaction stage Self-Elaboration

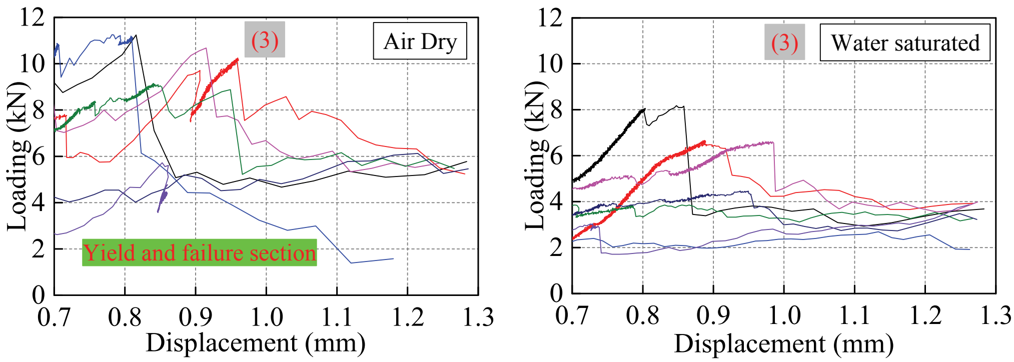
In the elastic stage (see Fig. 5), as β increases, the elasticity modulus of the shale shows a decrease trend in both the dry and water-saturated conditions. Moreover, water reduces the elasticity modulus of the shale significantly, and the softening phenomenon induced by the water mainly appears in the elastic stage.

In the failure stage, the value of the load fluctuated considerably during the failure process which lasted for a relatively long time. In the fracturing process, the rock specimen gradually lost its bearing capability. Especially in the water saturated condition, the shale specimen acquired long-term rheological properties after failure.



(a) Air dry condition (b) Water saturated condition

Fig. 5. Load versus displacement in the elastic stage Self-Elaboration



(a) Air dry condition (b) Water saturated condition

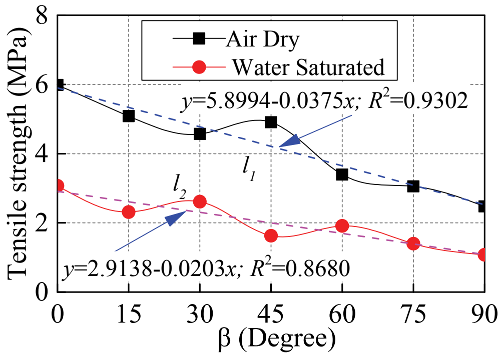
Fig. 6. Load versus displacement in the failure stage Self-Elaboration

(b) Brazilian tensile strength

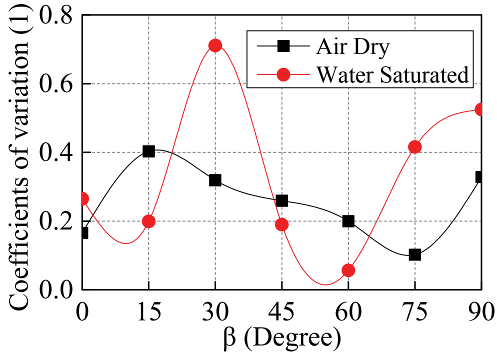
The different fracture angles resulted in different values of Brazilian splitting strength for both the dry and water-saturated conditions. With increasing fracture angles, the Brazilian splitting strength of the dry shale specimens were always larger those that of the water-saturated ones. l1 and l2 in Fig. 7 are the fitting straight lines of the tensile strength using the least squares method based on the results of the Brazilian split tests in dry and water-saturated conditions, respectively; the goodness of fit (R^2) of the two lines is 0.9302 and 0.8680, respectively. For both the dry and water-saturated conditions, the Brazilian splitting strength of the shale specimen decreased linearly with increasing β.

Figure 7b depicts the variation coefficient of the test data derived from the Brazilian split test with different values of β. The variation coefficient is 0.1-0.4 for the dry condition tests and 0.0-0.7 for the water-saturated tests, indicating that under wet conditions the test data has a relatively large discreteness and the experiment error increased. The relationship between the softening coefficient of the shale tensile strength and the fracture direction is shown as Fig. 7c.

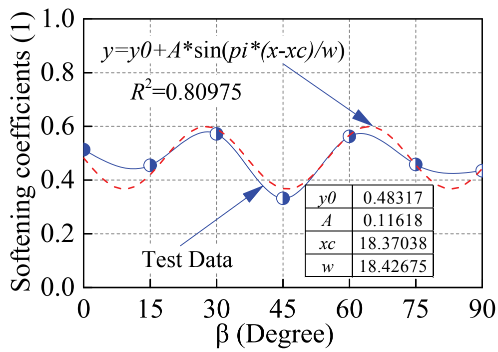
With increasing β, the softening coefficient fluctuates between 0.3 and 0.6. For $\beta = 45°$ and 30°, the softening coefficient reaches the minimum value, 0.33, and maximum value, 0.57, respectively. The data fitting shows that the softening coefficient presents a sine function change in the water-saturated condition with increasing β. The goodness of fit R^2 is 0.80975.



(a) Tensile strength relative to β



(b) Coefficients of variations relative to β



(c) Softening coefficients relative to β

Fig. 7. Brazilian tensile strength Self-Elaboration

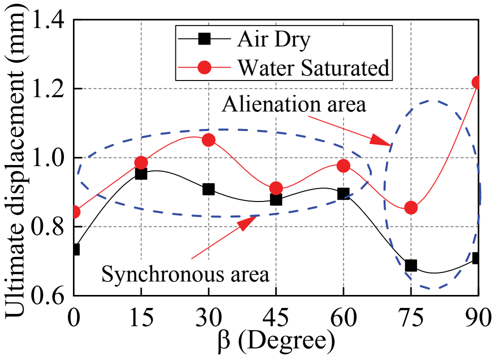
(c) Brazilian ultimate displacement

Based on the analysis in section 3.1, we conclude that the properties of the Brazilian split test are significantly affected by water and by the fracture angle. The vertical displacement associated with the ultimate load is defined as the ultimate displacement. In this section, the influences of β, and the dry and water-saturated conditions on the ultimate displacement are analyzed. The concept of the strengthening factor of the ultimate displacement is introduced to demonstrate that the ultimate displacement will increase when the rock is water-saturated.

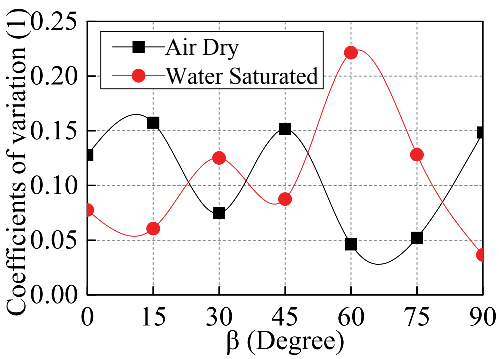
With increasing β, the ultimate displacement in water-saturated conditions is always larger than that in dry conditions. The ultimate displacement can be divided into two areas, namely the synchronous change area and the asynchronous change area. In the synchronous change area, with increasing β, the ultimate displacement in both dry and water-saturated conditions increases and then stabilizes the amplitude of the variation is similar for both cases. In the asynchronous change area, with increasing β, the ultimate displacement in dry conditions decreases and then stabilizes, while that in the water saturated condition first decreases and then rapidly increases.

With increasing β, the variation coefficient of the test data from the Brazilian split test fluctuates drastically as a whole. However, all the values are below 0.25, and the discreteness is small, indicating that the ultimate displacements of the five rock specimens in each sub-group are similar and the test data is credible.

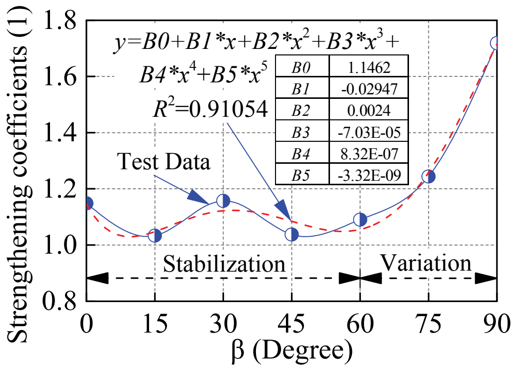
The strengthening factor of the ultimate displacement is always larger than 1 for all β values. The variation range can be divided into two areas: the stable area and the variable area. As β increases from 0i to 60ea the strengthening factor of the ultimate displacement is maintained between 1.0 and 1.2 and the amplitude of the variation is relatively small. This area belongs to the stable area. By contrast, as β increases from 0° to 60° the strengthening factor of the ultimate displacement increases considerably from 1.2 to 1.7; this area is the variable area. The data fitting shows that the strengthening factor of the ultimate displacement changes as a quartic polynomial with a goodness of fit $R^2 = 0.91054$.



(a) Ultimate displacement relative to β



(b) Coefficients of variations relative to β



(c) Strengthening coefficients relative to β

Fig. 8. Ultimate displacement Self-Elaboration

(d) Sample failure type

The standard Brazilian split test shows that specimens fracture into two parts along the diameter, and there is only one crack. For most of the specimens in our test, the failure mode of the standard Brazilian split test was observed; however, some of the specimens showed hybrid failure, combining tensile, compressive, and shear damage.

Figure 9 shows the classical failure images of the Brazilian split test. The failure characteristics of the rock specimens (1-4, 8, 10) are similar to those of the standard Brazilian split test. The crack of specimen 5 is not along the diameter direction, but has a certain angle to the load direction. Moreover, the bottom of the specimen is crushed, which means that the specimen failure was caused by tensile, compressive, and shear forced. Specimen 6 has two cracks: a radial crack and a non-radial crack. The non-radial crack bends to some extent, indicating tensile and shear forces. Specimens 7 and 9 have various fractures at the bottom of the specimen which are connected with the upper fracture. This indicates compressive and tensile damage.

Fig. 9. Failure types in the Brazilian test Self-Elaboration

(e) Verification of the proposed equations

The suggested formula for calculating the Brazilian tensile strength is shown as Eq. (1) (ASTM D3967-08, 2008), in which σt is the tensile strength of the Brazilian test, P is the damage load, D is the diameter of the specimen, and t is the thickness of the specimen.

Because of the different fracture angles, it is unrealistic to calculate the tensile strength of each rock specimen while conducting the tests. It can be seen from section 3.2 that the fitting formula (Eq. (2)) can reflect the Brazilian tensile strength influenced by β, and the fitting formula (Eq. (3)) can reflect the softening coefficient of the Brazilian tensile strength influenced by β.

$$\sigma_t = \frac{2P}{\pi D t} \tag{1}$$

$$\sigma_\beta = A + B\beta \tag{2}$$

$$s_\beta = s_0 + C\sin(\pi(\beta - \beta_c)/\text{w}) \tag{3}$$

When $\beta = 37°$, the Brazilian tensile strength is 4.7014 MPa and 2.0852 MPa for the dry and water saturated rock specimens, respectively. The strength softening coefficient is 0.443527. Substituting $\beta = 37°$ into the fitting formulas in Fig. 7a and c, the calculated Brazilian tensile strength is 4.7014 MPa and 2.0852 MPa for the dry and water saturated rock specimens, respectively. The strength softening coefficient is 0.443527. The corresponding deviation rate is 4.03%, 3.72%, and 8.03%, respectively, which meets the engineering application requirements. Therefore, the result from the fitting formula can estimate the Brazilian splitting tensile strength of dry shale at any angle.

Discussion

The Brazilian splitting process for shale specimens can be divided into three stages: the compaction, elastic, and failure stages. The compaction stage also includes two stages: partial compaction and creep deformation. The partial compaction stage lasts for a relatively short time and the curvature is relatively large. During the initial stage of the test, the specimen has a certain strength and stiffness. With the load increasing, the increment in the vertical displacement is marginal, about 0.025 mm. In the compaction stage, the specimen yields partially and damage may occur. The transition into the creep stage is rapid. With the partially damaged zone compacted, the vertical displacement increases from 0.025 mm to 0.4-0.6 mm. The fracture angle β has a significant influence on the curvature of the curve and the inflection point in each stage of the splitting process. For example, the curvature of the curve in the elastic stage under dry conditions is different, because the different values of β lead to changes in the properties of the rock specimen, including changes in the elasticity modulus and cohesion. In the water-saturated conditions, the difference in the curvature between the curves in the elastic stage decreases dramatically, which suggests that the effect of the water on the mechanical parameters of the specimen, such as elasticity modulus and cohesion, is smaller than the effect of the fracture angle. In the failure stage, the specimen develops long-term rheology properties (because the shale is not brittle), and the failure extends from the partial zone to the whole specimen.

The Brazilian tensile strength in the water-saturated condition is significantly lower than that in the dry condition, but with increased β, the strength in both conditions decreases linearly. The fracture in the shale specimen changes the Brazilian tensile strength, and the existence of water enhances the softening. Different values of β lead to different softening coefficients, with an average softening coefficient of 0.55. By using the data-fitting formula, the Brazilian tensile strength for any value of β can be estimated.

Based on previous research, to better explain the influence of the fracture angle and water on the Brazilian splitting characteristics, we introduce the concepts of the ultimate tensile displacement and the strengthening coefficient of the ultimate tensile displacement for Brazilian splitting. We show that the ultimate displacement shows an increase-stable-decrease-increase trend with increasing β. Water divides the ultimate displacement into two areas: synchronous area and alienation area. Correspondingly, the strengthening coefficient of the ultimate tensile displacement also has two areas: stabilization area and variation area.

The failure mode of the specimens generally coincides with the standard Brazilian splitting failure mode. Some of the specimens, however, have different failure modes: tensile-compressive, tensile-shear, or tensile-compressive-shear damage modes.

This study focuses on analyzing the effect of water and fracture angle on the Brazilian splitting process, splitting strength, ultimate displacement, and damage forms while the influence of the fracture density and moisture content on the Brazilian splitting strength will be studied in future work.

Conclusions

For many rock engineering projects, it is necessary to propose a failure criteria accounting for the transversely isotropic behaviors of rocks. Hence, it is very helpful to provide experimental data for the validation of the failure criteria. The paper presents the preparation method for transversely isotropic shale specimens and the experimental scheme for the Brazilian split test. The following conclusions can be drawn from our results.

The fracture angle β has a significant influence on the Brazilian splitting characteristics. With β increasing from 0° to 90° the compaction stage, elastic stage, and failure stage show variations in the curvature of the curve and inflection point. With increasing β, the tensile strength decreases linearly, and the ultimate displacement increases, then stabilizes, decreases, and finally increases again. Under water-saturated conditions, the ultimate displacement shows several failure modes. The failure mode of most of the specimens coincides with the standard Brazilian splitting failure mode while some specimens undergo hybrid failure modes.

The influence of water on the Brazilian split test mainly presents as a softening of the tensile strength, strengthening of the ultimate displacement, and creep deformation in the failure process. With increasing β, the softening coefficient of the tensile strength decreases, increases, and then decreases, with an average softening coefficient of 0.55. The strengthening coefficient of the ultimate tensile displacement is initially stable and then increases; the average strengthening coefficient is 1.2. Under water-saturated conditions, the shale specimen acquires rheological properties after failure. Based on the data fitting formulas, the tensile strength, softening coefficient, ultimate displacement, and strengthening coefficient can be calculated for any fracture angle.

For coal mine ground control, the surrounding rocks of interest generally show transversely isotropic behaviors. In addition, water would greatly influence the mechanical behavior and properties of rocks. To this point of view, the findings in this paper would greatly benefit coal mine ground control research.

Acknowledgments

This work is supported by the National Natural Science Foundation of China through contracts No. 51204166, 51174195, and 51474209 and also funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (SZBF2011-6-B35).

References

ASTM D3967-08, 2008. *International standard test method for splitting tensile strength of intact rock core specimens*. American Society for Testing and Materials, West Conshohocken.

Cai M., Kaiser P.K., 2004. *Numerical Simulation Of The Brazilian Test And The Tensile Strength Of Anisotropic Rocks And Rocks With Pre-Existing Cracks*. International Journal of Rock Mechanics and Mining Sciences, 41(3):478-483.

Coviello A., Lagioia R., Nova R., 2005. *On the Measurement of the Tensile Strength of Soft Rocks*. Rock Mechanics and Rock Engineering, 38(4):251-273.

Dan D.Q., Konietzky H., Herbst M., 2013. *Brazilian tensile strength tests on some anisotropic rocks*. International Journal of Rock Mechanics and Mining Sciences, 58:1-7.

Erarslan N., Williams D.J., 2012. *Experimental, numerical and analytical studies on tensile strength of rocks*. International Journal of Rock Mechanics and Mining Sciences, 49:21-30.

Hoek E., Brown E.T., 1980. *Underground excavation in rock*. London: Institution of Mining and Metallurgy, p: 157-162.

ISRM, 1978. *Suggested methods for determining tensile strength of rock materials*. International Journal of Rock Mechanics, Mining Sciences, and Geomechanics Abstract, 15(3):99-103.

Khanlari G., Rafiei B., Abdilor Y., 2014a. *An experimental investigation of the Brazilian tensile strength and failure patterns of laminated sandstones*. Rock Mechanics and Rock Engineer, 48(2):843-852.

Khanlari G.R., Heidari M., Sepahigero A.A., Fereidooni D., 2014b. *Quantification of strength anisotropy of metamorphic rocks of the Hamedan province, Iran, ad determined from cylindrical punch, point load and Brazilian tests*. Engineering Geology, 169:80-90.

Kulatilake P.H.S.W., Shou G., Huang T.H., Morgan R.M., 1995. *New peak shear strength criteria for anisotropic rock joints*. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 32(7):673-697.

Li D., Wong L.N.Y., Liu G., Zhang X.P., 2012. *Influence of water content and anisotropy on the strength and deformability of low porosity meta-sedimentary rocks triaxial compression*. Engineer Geology, 126:46-66.

Li W.F., Bai J.B., Peng S.S., Wang X.X., Xu Y., 2014. *Numerical modeling for yield pillar design: a case study*. Rock Mechanics and Rock Engineering, 48(1):305-318.

Li W.F., Bai J.B., Cheng J.Y., Peng S.S., Liu H.L., 2015. *Determination of coal-rock interface strength by laboratory direct shear tests under constant normal load*. International Journal of Rock Mechanics and Mining Sciences, 77:60-67.

Morsy K., Peng S.S., 2002. *Numerical modeling of the gob loading mechanism in longwall coal mines*. Proc. of the 21st International Conference on Ground Control in Mining, Morgantown, West Virginia, p: 58-67.

Peng S.S., 2007. *Ground Control Failures-A pictorial view of case studies*. West Virginia University, WV, p: 4-6.

Peng S.S., 2008. *Coal Mine Ground Control. Third Edition*. West Virginia University, WV, p: 359-363.

Qing Y.M., Dong C.X., Dong S.C., 2011. *Brazilian splitting strengths of discs and rings of rocks in dry and saturated conditions*. Chinese Journal of Rock Mechanics and Engineering, 30(3):464-472.

Su C., Zhang S., Tang X., 2013. *Experimental research on deformation and strength characteristics in process of Brazilian split fatigue failure of sandstone*. Chinese Journal of Rock Mechanics and Engineering, 32(1):41-48.

Suchowerska A.M., Merifield R.S., Carter J.P., 2013. *Vertical stress changes in multi-seam mining under supercritical longwall panels*. International Journal of Rock Mechanics and Mining Sciences, 61:306–320.

Tan X., Konietzky H., Fruhwirt T., Dan D.Q., 2014. *Brazilian tests on transversely isotropic rocks: laboratory testing and numerical simulations*. Rock Mechanics and Rock Engineering, 48(4):1341-1351.

Tien Y.M., Kuo M.C., Juang C.H., 2006. *An experimental investigation of the failure mechanism of simulated transversely isotropic rocks*. International Journal of Rock Mechanics and Mining Sciences, 43(8):1163-1181.

Yilmaz I., 2010. *Influence of water content on the strength and deformability of gypsum*. International Journal of Rock Mechanics and Mining Sciences, 47(2):342-347.

Wong L.N.Y., Jong M.C., 2014. *Water saturation effects on the Brazilian tensile strength of Gypsum and assessment of cracking processes using high-speed video*. Rock Mechanics and Rock Engineering, 47(4):1103-1115.

Received: 1 September 2015