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Experimental study on the confinement-dependent characteristics of a Utah coal considering the anisotropy by cleats

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ABSTRACT

Characterizing a coal from an engineering perspective for design of mining excavations is critical in order to prevent fatalities, as underground coal mines are often developed in highly stressed ground conditions. Coal pillar bursts involve the sudden expulsion of coal and rock into the mine opening. These events occur when relatively high stresses in a coal pillar, left for support in underground workings, exceed the pillar's load capacity causing the pillar to rupture without warning. This process may be influenced by cleating, which is a type of joint system that can be found in coal rock masses. As such, it is important to consider the anisotropy of coal mechanical behavior. Additionally, if coal is expected to fail in a brittle manner, then behavior changes, such as the transition from extensional to shear failure, have to be considered and reflected in the adopted failure criteria. It must be anticipated that a different failure mechanism occurs as the confinement level increases and conditions for tensile failure are prevented or strongly diminished. The anisotropy and confinement dependency of coal behavior previously mentioned merit extensive investigation. In this study, a total of 84 samples obtained from a Utah coal mine were investigated by conducting both unconfined and triaxial compressive tests. The results showed that the confining pressure dictated not only the peak compressive strength but also the brittleness as a function of the major to the minor principal stress ratio. Additionally, an s-shaped brittle failure criterion was fitted to the results, showing the development of confinement-dependent strength. Moreover, these mechanical characteristics were found to be strongly anisotropic, which was associated with the orientation of the cleats relative to the loading direction.

1. Introduction

Between 1983 and 2014, there were nearly 400 cases (208 in Utah, 88 in Colorado, 44 in Kentucky, 38 in West Virginia and 14 in Virginia) of reportable dynamic failure accidents in coal and other nonmetal mines, resulting in 20 fatalities, 155 lost-time accidents, and an estimated 48,000 lost man hours.[1] These events have been documented for well over 100 years within the American underground coal mining industry. Over this period of time, mining practices and support technologies have evolved considerably, resulting in an overall decrease in the rate of dynamic failure-related injuries and fatalities. Although mining techniques and practices are highly advanced, coal pillar bursts or bumps continue to occur. If coal is expected to fail in a brittle manner, behavior changes associated with relatively low tensile strength, such as the transition from tensile to shear failure, have to be considered and reflected in the adopted failure criteria. Rock failure in tension takes place at low confinement around excavations due to extensional cracking at the grain scale.[2] The prospect of tensile-fracture-dominated brittle failure diminishes as the confinement increases away from the excavation boundary. Therefore, it must be anticipated that the transition from tensile to shear mode in the failure mechanism occurs as the confinement level changes and the conditions for tensile failure are prevented or strongly diminished. The exact nature of this transition is likely to be influenced by the highly anisotropic characteristics of coal seams associated with geologic structure and the mining-induced spatial redistribution of stress in coal pillars.

This paper is developed as part of an effort by the National Institute for Occupational Safety and Health (NIOSH) to identify risk factors associated with bumps to prevent fatalities and accidents in highly stressed, bump-prone ground conditions. In this study, an experimental investigation by way of laboratory testing is used to characterize the engineering characteristics and brittleness of a coal. The engineering behavior of coal varies with respect to the angle between the geologic structure (i.e. cleating) and the loading direction (major principal

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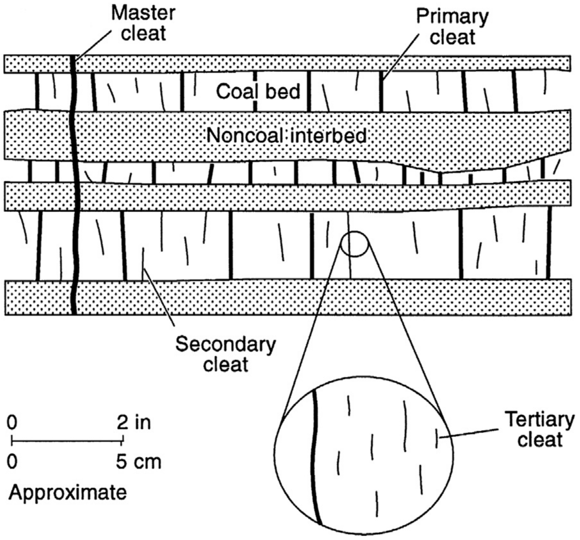

Fig. 1. Cleat hierarchies in cross section view (after Laubach et al.[6]).

stress). In this study, the angle between the cleat and the loading direction is referred to as the included angle. Various values of the included angle are considered as a testing parameter and are used to determine the confinement-dependent strength and brittleness; for this study, the Hoek-Brown constant (m_i)[3] and spalling limit ($k_{sp} = \sigma_1/y_3$) are used as indicators of brittleness.[4,5]

The next section discusses cleating in coal seams and its impact on the brittleness of coal. Afterward, the approach for the laboratory testing methods is described, including sample preparation and conditions. Finally, approaches that are appropriate for examining the strength and brittleness as a function of both confinement and orientation between cleat and loading direction are explained and demonstrated by means of the s-shaped brittle failure criterion proposed by Kaiser and Kim.[4,5]

2. Spatial characteristics of cleat and its role in engineering anisotropy of coal

Fractures exist in nearly all coal beds, and can exert fundamental control on coal stability, minability, and fluid flow. As illustrated in Fig. 1, cleats are fractures that usually occur in two sets that are, in most instances, mutually perpendicular and also perpendicular to bedding.[6]

Generally, cleats occur with spacing on a scale of only 1–6 cm. Many researchers have reported that the spatial characteristics of cleats in terms of their angle to the principal stress not only control global strength, but also impact the relative brittleness of the coal. Agapito and Goodrich[7] reported that Western dynamic failure events are typically associated with coals that are poorly cleated, indicating wider than usual spacing between cleat apertures. Hebblewhite and Galvin[8] noted localized variability in cleat distribution in conjunction with the location of the double-fatality coal burst at the Austar mine in Australia in 2014. In addition, the resultant anisotropy is influenced by the geometric relationship between the direction of mine development and the orientation of in-situ stress. Recently, Kim and Larson[9] numerically investigated a change of the stored elastic energy in the coal pillar and the plastic dissipated energy associated the underground exaction. The results of the numerical model showed that a change of the energy ratio significantly depended on the orientations of both the cleats and stresses. The numerical model results showed that the largest energy ratio occurred when at a specific orientation of cleats to the principal stress. In this study, therefore, anisotropic behavior of the coal associated with the orientation of cleats to principal stress is physically investigated as a function of confinement.

3. Sample preparation and testing methods

For this study, seventy-two triaxial tests and twelve unconfined compressive strength (UCS) tests were performed at Montana Tech in Butte, MT. A total of eighty-four cylindrical specimens were cored from several large Utah coal boulders, as shown in Fig. 2. The direction of cleating was determined from each coal boulder so that specimens with cleating at 0°, 15°, 30°, and 45° relative to the sample long axis could be obtained. A core drill was mounted on a hand-constructed frame that could support the large coal samples. A large mounting jig was constructed to hold the coal samples in the specific orientations relative to the drilling angle, as shown in Fig. 2. A water-cooled diamond bit was used to core twenty-one specimens from each of the four orientations.

All samples in this study were cored to an approximate diameter of 44 mm and cut to be within the ASTM (D 4543-08) recommended 2.0–2.5 length-to-diameter ratio. The ends of the specimen were ground on a surface grinder to be within the ASTM (D 4543-08) flatness tolerance of 0.025 mm. Specimen end flatness and perpendicularity tolerances were verified using a flatness testing gauge. The tests were performed on a TerraTek Model FX-S-33090 closed loop digital servo controlled load frame. The system was modified to incorporate two low-pressure (3.45-MPa) transducers to better control the low confining pressure (σ_3) required for this study, and to maintain a constant pressure throughout the test. The testing stack shown in Fig. 3 consisted of a TerraTek 113.4 t force load cell to measure force, two impervious endcaps, two Schaevitz MHR 500 LVDTs to measure axial displacement, a TerraTek radial cantilever transducer to measure lateral strain, and spherical seats to minimize risk of non-uniform loading of the specimen.

The seventy-two triaxial samples were jacketed with 0.5-mm-thick Dunbar-1635F flexible 2:1 Polyolefin to prevent the confining fluid from penetrating into the sample. The twelve UCS samples were tested without jackets. The triaxial test procedure followed the suggested method of ASTM (D7012), and the UCS tests were performed in accordance with ASTM (D7012). Both the triaxial and UCS test procedures were run under strain rate control with specimens axially loaded at a strain rate of 2.54×10^{-5} mm/mm/s.

A data processing approach introduced by Hoek[10] was used for detailed analysis of the triaxial test data to obtain the Hoek-Brown parameters, i.e., *m* and *s*. There are two critical factors that need to be considered when fitting data in this manner: (1) the confinement range should be at least one-half of the unconfined compressive strength of a rock, and (2) data are to be used for Hoek-Brown parameters with equal weighting over five equal increments of confining pressure. In order to satisfy these conditions and requirements, the confining pressures for the triaxial compressive tests were determined as a ratio of the unconfined compressive strength as shown in Table 1.

As recommended by Hoek and Brown[11] both Hoek-Brown parameters (σ_{ci} and m_i) were estimated by post-processing data using statistical analysis of the triaxial test data covering a confinement range up to half of *UCS* of intact rock in five equal increments. Accordingly, the unconfined intact rock strength (σ_{ci}) as a Hoek-Brown parameter is not obtained from unconfined compression tests, but determined by extrapolation from triaxial data by means of regression. In this paper, thus, we define the term *UCS* for data obtained from the unconfined tests on the coal samples, and y for the unconfined intact strength determined by the methodology proposed by Hoek.[10]