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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.

Keywords

Utah coal; Cleat; Anisotropy; S-shaped brittle failure criterion

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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 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)³ and spalling limit ($k_{sp} = \sigma_1/\gamma_3$) 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 Goodrich⁷ 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 Galvin⁸ 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 Larson⁹ 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 Hoek¹⁰ 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 Brown¹¹ 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

Per Kaiser and Kim^{4,5} for brittle rocks under low confinement, the *UCS* obtained from uniaxial compressive tests is typically substantially lower than the σ_{ci} obtained from triaxial tests. Furthermore, rocks failing in a brittle manner should exhibit a steeper rise in strength as a function of confining stress (also referred to as the spalling limit, $k_{sp} = \sigma_1/\sigma_3$) at lower confinement than that suggested by a standard Hoek-Brown fit obtained considering higher confinement triaxial data. Kaiser and Kim^{4,5} also demonstrated that because of these attributes of brittle rock strength, when interpreting laboratory test data and estimating representative strength parameters, the relevant confinement range should be considered. Parameters obtained by evaluating low confinement data should not be used for problems where the confined rock behavior is relevant. For example, the *UCS* provides a meaningful parameter for excavation wall stability assessment but not for the estimation of the strength of highly confined rock such as within a wide pillar. The consequence of this is that the standard Hoek-Brown parameter determination methodology may not lead to a strength envelope that is representative of the relevant rock strength behavior, depending on the range of confining stresses considered. For these reasons, the ranges of confinement in Table 1 were chosen to be from as small as 1% or 2% to as much as 50% of the unconfined compressive strength in order to allow for detailed consideration of both low-confinement and high-confinement strength trends.

4. Analysis of test results

4.1. Confinement-dependent strengths characterized by the S-shaped brittle failure criterion

The results of all specimens tested by both the unconfined and triaxial compressive tests in the present study are summarized in Appendix A. When a stress path not only reaches the relatively low confinement but also exceeds the damage threshold, crack and fracture coalescence result in spalling failure that is axial splitting with fractures parallel to the major principal stress (σ_1). For failure stress states in the low confinement zone, propagation and extension of fractures are strongly influenced by confinement. Lines of constant ratio of principal stress (σ_1/σ_3), called the spalling limit, indicate lines of equal coalescence potential. When a spalling limit is greater than 10, extensional cracking and spalling is likely to be the primary mode of failure.¹² As the brittle-ductile transition is approached (i.e. by increasing confinement), damage and deformation are concentrated in a shear failure zone characterized by localized small-scale extensional fracturing. While evidence of changes in failure mechanisms with confinement is common in the literature,^{4,5} the interpretation of test results in terms of failure criteria often neglects the transition of failure mode from tensile to shear; for instance, the Mohr-Coulomb failure criterion implies that a single mechanism defines the ultimate strength of the rock.⁵ The transition from axial splitting and spalling failure to shear failure typically occurs at confinement levels smaller than about 10% of unconfined compressive strength (*UCS*) of intact rock, as tensile crack propagation is inhibited for confinement levels larger than about $UCS/10$.¹³

The variation of the strengths and Hoek-Brown constant as a function of the included angle is presented in Figs. 4 and 5. An offset between *UCS* and σ_{ci} can be found in Fig. 4. Kaiser and Kim^{4,5} explained that this offset is observed for a wide number of rock types and is largest in cases where there is a significant change in failure modes (extensional versus shear failure) across the range of confining stresses considered. The unconfined coal strength and cohesion showed minimum values at 30° of the included angle whereas the Hoek-Brown constant presented its maximum values at the same included angle. This means that the most significant strength loss and frictional mobilization simultaneously occurred at 30° of the included angle, where shear along cleating was observed to be the dominant failure mechanism.

We also calculated conventional elastic and Mohr-Coulomb parameter values such as cohesion, internal friction angle, and tensile strength values were indirectly obtained using the methodology suggested by Hoek¹⁰ (see Appendix A). These have been studied elsewhere, however, and are not the main focus of this paper. The focus of this paper is on the strength and brittleness as characterized by attributes of a more appropriate strength criterion, the S-shaped criterion.^{4,5}

Kaiser and Kim^{4,5} introduced an s-shaped criterion for brittle rock strength as shown in Eqs. (1)–(3). The s-shaped criterion is presented here to illustrate the fact that strength in the low-confinement zone is disproportionately lower than in the high-confinement zone by an even greater margin than typically predicted by more conventional strength models (i.e. Hoek-

Brown). This phenomenon is the result of changes in the failure mode for brittle rocks with extensional failure at low confinement and shear failure at high confinement.

$$\sigma'_1 = k_2 \sigma'_3 + AUCS + \frac{(UCS - AUCS)}{1 + e^{\left(\sigma'_3 - \frac{\sigma_3^0}{\delta \sigma_3}\right)}} \quad (1)$$

where UCS , the lower y -intercept, is the unconfined compressive strength obtained from the laboratory test; $AUCS$ is the y -intercept obtained from the linear back projection of a linear fit to high confinement data; and k_2 is the gradient of this high confinement linear fit. Therefore, the UCS represents intact rock strength at low confinement, whereas the $AUCS$ can be estimated as the unconfined component of intact rock strength (i.e. analogous to cohesion) at high confinement.

The transition curve from lower confinement to higher confinement region is called the spalling limit and is assumed to start at the origin with a slope of $k_s = \sigma_1/\sigma_3$.^{4,5}

$$\sigma_3^0 = \frac{(UCS - AUCS)}{2(k'_s - k_2)}, \quad \left(k_s = \frac{\sigma'_1}{\sigma'_3}\right) \quad (2)$$

$$\delta \sigma_3 = C \sigma_3^0, \quad (C = 0.1 \sim 0.3) \quad (3)$$

The S-shaped criterion fitting procedure was implemented in a spreadsheet using the equations to produce the example presented in Fig. 6. The figure shows the results of the s-shaped criterion fit to all the triaxial compressive tests for the coal specimens regardless of the included angle. All the parameters for Eq. (1) were calculated as shown in the legend. The regression coefficient, r^2 , was calculated to be approximately 0.71. There was a dispersion of the data particularly at the low confinement. However, the dispersion probably resulted because the coal was a very heterogeneous material and the development of cleating in the coal varied greatly; this resulted in different modes of failure occurring at low levels of confinement, even for a constant value of the included angle. Fig. 7 presents the photographs that were taken after the test showing the failure mode of the coal specimens. Fig. 7(a) presents that the matrix mainly broke in the specimen whereas Fig. 7(b) shows that the failure primarily occurred along the plane of cleat. This transition from variable failure modes at low confinement to a more consistent shear mechanism at higher confinement necessitates the use of the s-shaped criterion to fit the results of the test for estimation of a ratio of $AUCS$ to UCS . This curve is generally developed through the middle of the data starting with the mean value of the UCS regardless of the failure mode.

In order to look into the dispersion of the data, Fig. 6 was re-generated with prediction limit curves. Fig. 8 (the entire range of the confinement) and Fig. 9 (at the low confinement, < 2.5 MPa) show that the solid line of the S-shaped curve was fit along the data starting with the mean UCS of all the test results as a constraint on the fitting process. Both the dashed and the dot-dashed lines were generated based on a two-sided prediction interval with 95% confidence. Although the data show some scatter located outside of the prediction limits between 0.25 and 0.5 MPa of the confinement, most of the data are located within the prediction limits. In this study, the brittleness is represented by the spalling limit (k_{sp}), which is a ratio of major to minor principal stress (σ_1/σ_3). The average spalling limit (σ_1/σ_3) regardless of the included angle was estimated as 36.3.

Fig. 10 presents the results of fitting the S-shaped criterion to data from the specimens with an angle of 0°, 15°, 30°, and 45° of the included angle, respectively. All the curves in the figure represent the s-shaped curve based on the average UCS for each case. It is evident that the confined peak strength is very significantly increased relative to the unconfined strength, even at the lowest confinement levels, which are 1–2% of the unconfined compressive strength. The values of the spalling limit estimated in this study were generally higher than the spalling limit of an Australian coal at 38¹⁴ and of an Chinese coal at 40.¹⁵

Kaiser and Kim^{4,5} presented the different parameters that dominate rock behavior in their s-shaped brittle failure criterion that includes linear and sigmoidal components as shown in Fig. 8: UCS near excavation walls and apparent compressive strength ($AUCS$) in low-confinement conditions that are typically encountered at a distance of less than one radius from the excavation wall. UCS is the lower y -intercept of the formula, the unconfined compressive strength obtained from the laboratory test; $AUCS$ is the y -intercept obtained from the back-projection of a linear fit to high confinement data. In this study, the $AUCS$ is the y -intercept obtained based on the triaxial data for 10% and 50% of the confinement. It is observed that the $AUCS$ of the coal was found to be over 70% greater than the UCS if the applied confinement to the coal was as much as 10% of the UCS . The ratio of ACS to UCS for the different conditions of the included angle are presented in Table 2. It was also observed that axial splitting can be suppressed by very low confinement, which is equivalent to 1% of the unconfined compressive strength. This means that a small amount of confinement provided by an appropriate rib support system would be able to prevent spalling (or slabbing) due to the tensile failure mechanism controlled by a lower confinement at the boundary of underground excavations. In other words, the ultimate coal strength near a longwall face or the surface of a coal pillar can be significantly decreased if confinement is lost. This strength loss is likely to be more than that anticipated by classical failure criteria that do not consider such an appropriate characterization of confinement-dependent strength.

Following the procedure of data interpretation using the S-shaped failure criterion proposed by Kaiser and Kim^{4,5} the anisotropic spalling limit of the coal specimens is illustrated in Fig. 11. Similarly to the Hoek-Brown m_i parameter, the spalling limit was found to be greatest for the included angle of 30°; both these results suggest that the coal was the most brittle under this condition. This is also in agreement with the numerical modelling-based findings of Kim and Larson.⁹

4.2. Damage characteristics of the coal samples

In addition to the peak strength and values, the crack initiation (CI) and crack damage (CD) stress thresholds were estimated. These thresholds correspond to the onset of systematic stable and unstable cracking in intact rock, respectively.¹⁶ Based on laboratory testing, these values are defined as the stresses at which the lateral and axial strain curves deviate from linearity with respect to variations in axial stress. For this study, the point of lateral strain nonlinearity (CI) was identified based on the crack volumetric strain reversal point; crack volumetric strain was calculated by subtracting elastic volumetric strain (calculated based on the data-derived elastic moduli for each specimen) from total volumetric strain, leaving only the crack-related component of volumetric strain.¹⁷ The point of axial strain nonlinearity (CD) was identified as the point at which the tangent modulus begins to decrease from its constant, maximum value (corresponding to the Young's modulus).^{16,18,19}

The CI results obtained are shown in Fig. 12. The CI results for all included angle cases are plotted together, as any variations as a function of included angle were found to be statistically insignificant relative to the natural variability in the results obtained (ANOVA p-value = 48% from a comparison of unconfined CI values). This result is consistent with the finding of Ghazvinian et al.²⁰ from a study of several anisotropic rocks that CI is a relatively anisotropy-insensitive damage threshold.

The data acquired show that CD is much more dependent on the included angle than CI (see Fig. 13), which is again consistent with the findings of Ghazvinian et al.²⁰ As in the case of the peak strength, the 30° included angle results show a much lower CD than the other cases, with the 0° included angle tests having the highest CD values. The variations in the individual Hoek-Brown fit parameters (unconfined fit value and m_i) for CD at different included angles are shown in Fig. 14. While the m_i values show minimal variation and no clear trend, the unconfined CD fit values show a clear trend which matches that of the unconfined peak strength fit values shown in Fig. 4.

4.3. Post-yield dilatancy of the coal samples

The tendency of rock to increase in volume following yield (referred to as dilatancy) has long been established as a fundamental material characteristic.²¹ Many recent studies have examined the complexities of dilatancy for isotropic rocks, such as the effect of confining stress in reducing the amount of dilatancy which occurs and the effects of progressive damage on the mobilization and, ultimately, decay of dilatancy.^{22–24} The authors are not aware, however, of any comprehensive studies on the impact of rock fabric anisotropy of dilatancy; most of the existing data on anisotropic dilatancy presented in the literature focus on joint dilatancy rather than intact rock matrix dilatancy, (e.g.²⁵) or treat dilatancy in a simplified manner, ignoring the complexities mentioned above.(e.g.²⁶)

To qualitatively assess whether or not the dilatant characteristics of the coal being studied are at all anisotropic in nature, one can examine the volumetric strain-axial strain plots for the different included angles considered. In Fig. 15, the volumetric strain values at each axial strain have been averaged for all specimens with the same confining stress and are presented separately for each included angle. In examining the results for any of the included angles

tested, the confinement dependency of dilatancy can be clearly seen in terms of both the decrease in maximum volumetric expansion rate at higher confining stresses as well as the lower amount of total dilatancy at the point of sample rupture (i.e. at the end of each test). With respect to dilation anisotropy, a comparison of the plots shown for different included angles considered reveals that there is indeed relatively large variability between the amount of volumetric expansion observed in each case.

To examine the potential anisotropy in the dilatancy of the coal further, it is necessary to parametrize this phenomenon. A commonly used parameter to describe the dilatancy of rock is the dilation angle, ψ ²⁷; generally speaking, higher dilation angle values correspond to a greater amount of post-yield volumetric expansion. Although the dilation angle was historically treated as a constant parameter, several authors have demonstrated that more generally, the dilation angle should be considered a function of both the confining stress and damage state of rock, typically represented by the maximum plastic shear strain, γ^p (i.e. $\psi = \psi(\sigma_3, \gamma^p)$). Several models have been proposed to represent variations in the dilation angle of rock.^{22–24} The general procedure for studying dilatancy in the context of such models is as follows. First, determine plastic strain values at several points throughout the test; plastic strains can be estimated from the total strain data recorded through removal of a calculated elastic strain component.²⁸ Second, estimate the instantaneous dilation angle values at each of these points. The dilation angle can be calculated as

$$\sin(\psi) = \frac{\dot{\epsilon}_v^p}{-2\dot{\epsilon}_1^p + \dot{\epsilon}_v^p} \quad (4)$$

where $\dot{\epsilon}_v^p$ is the plastic volumetric strain increment and $\dot{\epsilon}_1^p$ is the major principal (axial) plastic strain increment.²⁷

Third, for each individual specimen, fit an equation of the form $\psi = \psi(\gamma^p)$ to the results.^{23,24} Lastly, using the fit parameters from each of the individual specimens and their corresponding confining stresses, determine which model parameters constrain the influence of confining stress on dilatancy.^{23,24}

In this study, the model of Walton & Diederichs²⁴ has been used to analyze the results. This model uses four parameters to fit a function of the form $\psi = \psi(\gamma^p)$ to the dilation angle data from each specimen. Although any of these four parameters can be considered to be dependent on confining stress, for practical purposes, most of them are considered to be constant; only the peak dilation angle, ψ_{Peak} , consistently demonstrates any notable confinement dependency.^{24,29–32} The peak dilation angle represents the maximum instantaneous dilation angle for the specimen.

When examining the model results for the coal being studied, none of the parameters demonstrated any consistent confinement dependency other than the peak dilation angle. Additionally, the peak dilation angle was the only model parameter which showed any variation as a function of the included angle. As shown in Fig. 16, the peak dilation angle

decreases as a function of confining stress most rapidly for the tests conducted with the included angle of 30°. This suggests that even under modest levels of confining stress, the overall dilatant tendency of the coal when loaded with an included angle of 30° will tend to be lower than when it is loaded with an included angle of 0°. This is in agreement with the suggestion of Hoek and Brown¹¹ that dilatancy tends to be loosely correlated with strength.

To better quantify the degree of anisotropy in the peak dilation angle's confining stress dependency, we can consider the model applied to capture this trend as shown in Fig. 16:

$$\frac{\psi_{Peak}}{\phi_{Peak}} = 1 - \frac{\beta'}{e^{-(1-\beta_0-\beta')/\beta'}} \sigma_3 \quad (5)$$

In this equation, β_0 is a parameter that controls the confining stress dependency of the peak dilation angle at low confining stress, β' is a parameter that controls the confining stress dependency of the peak dilation angle at higher confining stresses.²⁴ In the case of the results shown in Fig. 17, the β_0 values vary much more than the β' values. Large values of β_0 correspond to a small drop in peak dilation angle with increased confining stress, whereas small values of β_0 correspond to a large drop in peak dilation angle with increased confining stress. The anisotropy in peak dilation confining stress sensitivity can be clearly seen by considering the changes in β_0 as a function of included angle (see Fig. 17). The lowest value of β_0 for the included angle of 30° suggests that for this included angle (for which the specimens are weakest), the peak dilation angle is very sensitive to the confining stress applied. This is consistent with the observed failure mechanism: the shearing along relatively planar cleat surfaces which occurs at an included angle of 30° can occur without significant dilation much more readily than highly dilatant axial cracking through intact coal which occurs for an included angle of 0°. This tendency of shear failures to be less dilatant than failures dominated by axial cracking has been previously observed for other rock types.²⁴

5. Conclusions

In this study, a laboratory investigation using both unconfined and triaxial compressive tests that examines the strength, brittleness, and dilation anisotropy of a Utah coal is presented. Four orientations between the cleat and axial loading direction in the coal specimen were considered as a testing parameter.

In summary, the following are the main results of the experimental investigation by the laboratory tests. The spalling limit of the coal estimated by the s-shaped brittle failure criterion appears to be very dependent on the angle between the cleat and the loading direction. The range of the spalling limit was observed to be from 36 to 57. The peak strength and crack damage (CD) envelopes were found to be highly anisotropic; in contrast to this result, the crack initiation (CI) envelope was relatively insensitive to the angle between the loading direction and primary cleat orientation. The peak strength increased by as much as 40–50% of the mean unconfined compressive strength with confining stresses as

low as 1% of the unconfined compressive strength applied. The dilation behavior of the coal was found to be anisotropic; in particular, this anisotropy of dilatancy was found to be primarily associated with the peak dilation angle and its sensitivity to confining stress. Since the coal showed that the mechanical characteristics are strongly anisotropic and confinement-dependent, a better characterization of coal for the analysis and design of excavations and pillars is an important step toward improving miner safety with respect to stability of underground workplaces and the prevention of fatalities.

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Appendix A

See Appendix Tables A1 and A2

Table A1

Summary of the results of the compressive tests.

Included angle (0°)		Included angle (15°)		Included angle (30°)		Included angle (45°)	
Confining pressure (σ_3 , MPa)	Peak stress (σ_1 , MPa)	Confining pressure (σ_3 , MPa)	Peak stress (σ_1 , MPa)	Confining pressure (σ_3 , MPa)	Peak stress (σ_1 , MPa)	Confining pressure (σ_3 , MPa)	Peak stress (σ_1 , MPa)
0.00	15.01	0.00	18.45	0.00	5.39	0.00	8.95
0.00	22.44	0.00	19.02	0.00	7.72	0.00	14.62
0.00	40.29	0.00	19.81	0.00	17.68	0.00	30.37
0.22	35.54	0.19	23.29	0.08	2.99	0.14	10.74
0.22	37.28	0.19	32.18	0.08	11.97	0.14	19.57
0.22	38.70	0.19	34.00	0.08	18.07	0.14	21.09
0.44	35.12	0.38	25.71	0.15	13.10	0.29	10.24
0.44	46.07	0.38	35.50	0.15	13.57	0.29	33.99
0.44	50.58	0.38	36.07	0.15	22.40	0.29	37.90
0.67	32.45	0.57	27.43	0.23	10.25	0.44	24.59
0.67	34.70	0.57	39.74	0.23	12.20	0.44	24.75
0.67	40.29	0.57	42.70	0.23	15.58	0.44	27.97
1.46	37.84	1.24	29.91	0.50	7.55	0.95	23.94
1.46	50.89	1.24	39.67	0.50	22.81	0.95	32.19
1.46	53.14	1.24	39.90	0.50	23.81	0.95	41.35
2.24	45.28	1.90	40.20	0.77	10.52	1.46	22.81
2.24	47.37	1.90	42.11	0.77	16.20	1.46	26.98
2.24	51.81	1.90	54.17	0.77	17.27	1.46	30.76
11.22	59.92	9.51	73.20	3.86	28.92	7.31	44.27
11.22	91.00	9.51	81.88	3.86	34.97	7.31	64.34
11.22	95.20	9.51	91.10	3.86	35.20	7.31	74.28

Table A2

Summary of the average mechanical properties.

	Included angle (0°)	Included angle (15°)	Included angle (30°)	Included angle (45°)
Young's modulus (E , GPa)	3.6	3.5	2.4	2.9
Poisson's ratio (ν)	0.39	0.30	0.29	0.28
Cohesion (c , MPa)	6.7	5.4	2.2	4.1
Internal friction angle (ϕ , degrees)	45.5	47.0	47.6	45.8
Tensile strength (σ_t , MPa)	2.1	1.4	0.6	1.2

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

Fig. 2. Preparation of a recovered specimen considering the included angle of 15° ((a) and (b)), the tilted coal sample ready for coring ((c) and (d)).

Fig. 3.
Experimental configuration of both the unconfined and confined compressive tests.

Fig. 4.
Average of coal strength as a function of the included angle.

Fig. 5.
Estimated Hoek-Brown constant as a function of the included angle.

Fig. 6.
Example of the curve fitting on the s-shaped brittle failure criterion.

Fig. 7. Examples of failed coal samples with 30° included angle after unconfined compressive strength testing: (a) an example of a specimen failed primarily through the matrix material; (b) an example of a specimen failed primarily along a pre-existing cleat structure.

Fig. 8.
Results of all the triaxial compressive tests fitted with the s-shaped criterion with 95% prediction limit curves shown.

Fig. 9.

Results of all the triaxial compressive tests fitted with the s-shaped criterion at the low confinement (< 2.5 MPa) with 95% prediction limit curves shown.

Fig. 10.

Results of triaxial compressive tests (a: 0° of the included angle; b: 15° of the included angle; c: 30° of the included angle; and d: 45° of the included angle;) fitted on s-shaped brittle failure criterion.

Fig. 11.
Calculated spalling limits as a function of the included angle.

Fig. 12.

Crack initiation stress (CI) values for all included angles and linear fit ($\sigma_1 = 1.83\sigma_3 + 4.95$) to all values except the outlier at (11.2,67.8).

Fig. 13. Crack damage stress (CD) values for all included angles and associated intact Hoek-Brown fits.

Fig. 14. Unconfined crack damage stress (CD) (a) and m_i (b) Hoek-Brown fit parameters to crack damage stress (CD) values for different included angles.

Fig. 15.

Average volumetric strain-axial strain plots for different levels of confining stress. Curves are shown for included angles of 0° (a), 15° (b), 30° (c), and 45° (d). Note that the vertical axis values vary.

Fig. 16.
Peak dilation angle values for different included angles.

Fig. 17.

Values of β_0 from the WD (Walton and Diederichs²⁴) dilation angle model as a function of included angle. Lower values indicate a higher sensitivity of the peak dilation angle to confining stress at low confining stress values.

Table 1

Determination of the levels of the confinement for the confined compressive test.

Ratio of confining pressure to UCS	Anticipated failure mode (Kaiser and Kim ^{4,5})
1.0%	Extensional
2.0%	Extensional
3.0%	Transitional
6.5%	Transitional
10.0%	Shear
50.0%	Shear

Table 2Calculations of the ratio of apparent *UCS* (*AUCS*) to *UCS*.

	<i>AUCS/UCS</i>
All	1.74
0°	1.65
15°	1.91
30°	1.93
45°	2.46