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Experimental and numerical study on the effect of calcite on the mechanical behaviour of coal

Fuqiang Gao *, Hongpu Kang, Yongzheng Wu

[a] State Key Laboratory of Coal Mining and Clean Utilization, China Coal Research Institute, Beijing, China
[b] Mining & Designing Branch, China Coal Research Institute, Beijing, China

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ABSTRACT

The effects of the presence of calcite grains on the mechanical behaviour of a coal are investigated in this study. Coal specimens with and without calcite grains were obtained from the same coal seam and then subjected to confined compression with varying confining pressures. Mineral composition data of the coal containing calcite grains were obtained from petrographic analysis and subsequently used for constructing UDEC-GBM model. The model was calibrated to experimental results and then used to further the understanding of the influence of calcite grains on the mechanical behaviour of the coal. It is found that the presence of calcite increases the Young's modulus, reduces the peak strength and the brittleness of the coal. The numerical results suggest that the presence of calcite grains significantly increase the heterogeneities of the coal, leading to differential and extensional straining which in turn causes internal tensile stresses and consequently tensile cracking. The conformity of the numerical results with the experimental observations suggests the potential use of the UDEC-GBM approach model for better understanding the mechanics of brittle rock failure at micro-structure scale.

1. Introduction

Mineral formations in coal are complex and are controlled by many factors including source rocks, lithology, degree of weathering, nature of the coal-forming environment, hydrology, conditions of burial and degree of coalification (Dawson et al., 2012). The mineral formations of coal seams are not static and may evolve from deposition to the present day. Common minerals in coal include kaolinite, quartz, illite, pyrite, jarosite, melanterite, gypsum, rutile, and calcite. Knowledge about the mineral composition of coal is relevant to many aspects of coal from production to utilization. Numerous studies have been performed to investigate the effects of the mineral composition and microstructure of coal on many aspects including the design and selection of fluids for drilling and production of coal bed methane (CBM) (Karacan and Okandan, 2000), CO_2 sorption (Karacan, 2007; Karacan and Mitchell, 2003), coal clean process and human health (Cutruneo et al., 2014; Dai et al., 2004; Finkelman et al., 2002; Huggins et al., 2012), and concentration of trace elements (Sutcu and Karayigit, 2015; Ward, 2002). Very few studies have focused on the effect of mineral composition on the mechanical behaviour of coal. Using optical microscopy, scanning electron microscopy with energy dispersive X-ray spectrometry, and X-ray computed tomography, Cai et al. (2015) performed an experimental study on coal samples to investigate the effect of mineral matter on the fracture evolution. They found that the difference in density between coal matrix and mineral matter may weaken the cohesion of the coal. Espinoza et al. (2016) investigated the fracture patterns of a coal sample subjected to deviatoric loading. They used X-ray microtomography to examine the natural and induced fractures before and after loading and found that the mineralized veins can intensify stresses around tips, localize fracture propagation and promote brittle failure behaviour. It is well documented that the mechanical behaviour of rock materials in coal mine depends to a great extent on the mineral components and the way in which they are packed together (Ward et al., 2005). For other coal measures including sandstone, siltstone and shale, the petrographic features (i.e. mineral composition, fabric, degree of grain interlocking, quartz content, matrix content) are intrinsic properties and control the mechanical behaviour of the rocks at the fundamental level (Phillipson, 2008; Singh et al., 2001).

In this study, the effects of the presence of calcite grains on the mechanical behaviour of a coal were examined. Coal specimens with and without calcite grains were obtained from the same coal seam. Confined compression tests with varying confining pressures were performed on the coal specimens. A grain-breakable discrete element model was

* Corresponding author at: State Key Laboratory of Coal Mining and Clean Utilization, China Coal Research Institute, Beijing, China.
E-mail address: fuqgao@gmail.com (F. Gao).

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constructed based on the mineral composition data of the calcite coal that were obtained from petrographic analysis. The model was calibrated to experimental results and then used to further the understanding of the influence of calcite grains on the mechanical behaviour of the coal.

2. Laboratory tests

The coal samples used in the study were obtained from block cutting in the #5 coal seam at the Hejiata Coal Mine, China. The thickness of the coal seam ranged from 2.4 to 3.8 m. The long flame coal contains 5.56 to 10.38% ash, 69.8% carbon, 0.23% sulphur, and 8.29 to 9.14% moisture. Calcite grains were visible in parts of the coal. For the objective of this study, two groups of coal specimens were prepared depending on the presence of calcite. Specimens in Group 1 contained visible calcite throughout the specimens and were referred to as calcite coal specimens, specimens in Group 2 did not contain visible calcite and were referred to as regular coal specimens, see Fig. 1. A total of 18 Group 1 specimens and 25 Group 2 specimens were prepared by means of laboratory core drilling in the direction perpendicular to the bedding planes. All the specimens were cylindrical, 50 mm in diameter and 100 mm in length. The ends of the specimens were carefully surfaced using a rotating grinding device to ensure that the two surfaces were parallel to one other tested. The specimens were jacketed with 3 mm thick soft rubber to prevent pressure fluid from entering the specimens during confined compression tests.

For each group of coal specimens, compression tests were performed under confined conditions with confining pressures of 0.5, 1.0, 2.0, 3.5, and 5.0 MPa. The specimens were loaded on a digital servo-controlled testing machine with a 3000 kN capacity. The axial load was applied at a significantly small constant strain rate of 10–5 s^{-1} to ensure a stable failure process. The specimens' strains were determined by displacement measurements using axial and lateral displacement transducers.

Table 1 lists the results of all the coal specimens tested in the present study. For each group of coal specimens, the confining pressures and the corresponding peak strength values were plotted and a strength envelope was obtained by linear regression, see Fig. 2. The gradient *m* and the Y-axis intercept *b* were then obtained and used for calculating the internal friction angle ϕ and cohesion *c* of the coal, using the following equations (Kovari et al., 1983):

$$\phi = \arcsin\frac{m-1}{m+1} \tag{1}$$

$$c = b\frac{1-\sin\phi}{2\cos\phi}. \tag{2}$$

The following conclusions with emphasis on the influence of calcite can be drawn from the experimental study:

- For both calcite and regular coal specimens, no evident increase in Young's modulus was observed as the confining pressure increased from 0.5 to 5.0 MPa.
- The calcite grains have a significant effect on the deformability of the coal, see Fig. 3. The calcite coal has greater Young's modulus (average 3.4 GPa) than the regular coal (average 2.6 GPa).
- The presence of calcite appears to decrease the frictional component of strength and increase the cohesional component of strength of the coal. The derived cohesion and internal friction angle for the calcite coal specimens were 10.7 MPa and 34.0°, respectively, compared to 8.4 MPa and 43.6° for the regular coal specimens.

Table 1
Summary of test results for coal specimens.

Specimen no.	E_t (GPa)	υ	σ_3 (MPa)	σ_l (MPa)
P1-1	3.0	0.29	0.5	44.0
P1-2	3.8	0.30	0.5	40.2
P1-3	3.1	0.31	0.5	30.5
P1-4	3.1	0.29	0.5	43.5
P2-1	3.4	0.26	1.0	48.7
P2-2	3.5	0.26	1.0	42.4
P2-3	3.7	0.37	1.0	45.5
P2-4	2.8	0.35	1.0	41.5
P3-1	3.4	0.33	2.0	43.2
P3-2	3.1	0.27	2.0	51.4
P3-3	3.3	0.37	2.0	50.4
P3-4	2.9	0.35	2.0	54.0
P4-1	3.6	0.38	3.5	54.0
P4-2	4.2	0.25	3.5	50.0
P4-3	3.5	0.11	3.5	58.5
P5-1	3.8	0.32	5.0	48.3
P5-2	3.2	0.21	5.0	56.8
P5-3	3.5	0.25	5.0	62.4
S1-1	2.4	0.30	0.5	45.7
S1-2	2.4	0.30	0.5	41.3
S1-3	2.7	0.36	0.5	36.4
S1-4	2.6	0.32	0.5	40.7
S1-5	2.3	0.30	0.5	34.6
S2-1	2.5	0.31	1.0	39.7
S2-2	2.5	0.30	1.0	49.5
S2-3	2.3	0.30	1.0	42.0
S2-4	2.2	0.29	1.0	33.4
S2-5	2.6	0.34	1.0	51.8
S3-1	2.6	0.17	2.0	49.7
S3-2	2.4	0.30	2.0	46.8
S3-3	2.5	0.31	2.0	49.9
S3-4	2.4	0.30	2.0	55.0
S3-5	2.8	0.35	2.0	62.5
S4-1	3.1	0.30	3.5	57.1
S4-2	2.9	0.40	3.5	53.5
S4-3	2.3	0.27	3.5	60.3
S4-4	2.4	0.30	3.5	70.3
S4-5	2.8	0.35	3.5	61.4
S5-1	2.6	0.34	5.0	64.5
S5-2	2.8	0.35	5.0	72.3
S5-3	2.5	0.31	5.0	67.3
S5-4	2.5	0.34	5.0	53.7
S5-5	2.9	0.36	5.0	59.5

E_t = tangent Young's modulus, υ = Poisson's ratio, σ_3 = confining stress, σ_l = peak strength.
Specimen no. with letter "P" indicates Group 1 specimens containing calcite.

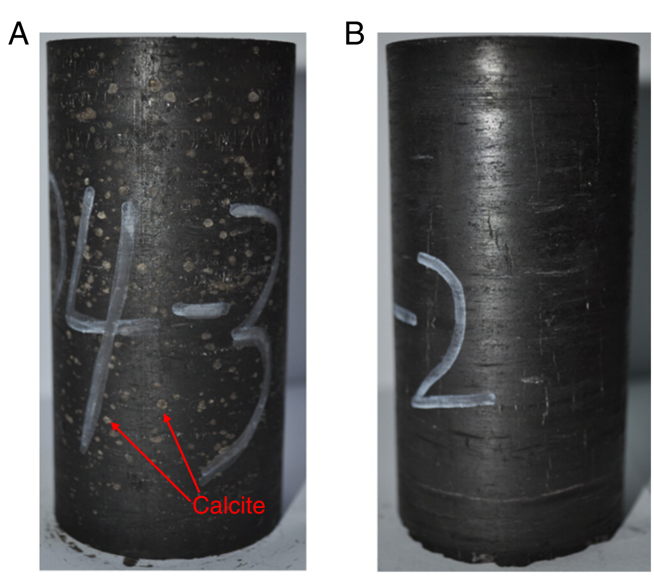

Fig. 1. Examples of coal specimens used in this study. (A) Group 1 specimen containing calcite, and (B) Group 2 without calcite.