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Change of the mode of failure by interface friction and width-to-height ratio of coal specimens

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ABSTRACT

Bumps in coal mines have been recognized as a major hazard for many years. These sudden and violent failures around mine openings have compromised safety, ventilation and access to mine workings. Previous studies showed that the violence of coal specimen failure depends on both the interface friction and width-to-height (W/H) ratio of coal specimen. The mode of failure for a uniaxially loaded coal specimen or a coal pillar is a combination of both shear failure along the interface and compressive failure in the coal. The shear failure along the interface triggered the compressive failure in coal. The compressive failure of a coal specimen or a coal pillar can be controlled by changing its W/H ratio. As the W/H ratio increases, the ultimate strength increases. Hence, with a proper combination of interface friction and the W/H ratio of pillar or coal specimen, the mode of failure will change from sudden violent failure which is brittle failure to non-violent failure which is ductile failure. The main objective of this paper is to determine at what W/H ratio and interface friction the mode of failure changes from violent to non-violent. In this research, coal specimens of W/H ratio ranging from 1 to 10 were uniaxially tested under two interface frictions of 0.1 and 0.25, and the results are presented and discussed.

1. Introduction

Coal mine bumps are sudden, violent bursts of coal from a pillar or pillars or a block of coal, resulting in a section, the whole pillar, or the solid block of coal being thrown into an open entry. These bursts are accompanied by very loud noises (Peng, 2008). Several case histories in mining have long coal pillars or coal faces failing violently with an accompanying ejection of debris and broken material into the working areas of the mines (Peperakis, 1958; Osterwald, 1962; Campoli et al., 1987; Garvey and Ozbay, 2013). Because of the catastrophic nature of these sudden failures, understanding the causes of coal mine bumps is essential to create a safe underground working environment. This phenomenon has motivated many ground control researchers to conduct extensive field investigations throughout the past century. Rashed and Peng (2014) compared the mechanical properties of two kinds of coal, one from bump and the other from non-bump prone mines. They found that coal itself does not play any significant role in coal bumps and recommended that future research should focus more on the local variation of geological conditions such as the interface friction between pillar and roof and between pillar and floor.

Some researchers (Holland, 1958; Campoli et al., 1987; Iannacchione and Zelanko, 1994) agreed that the geological conditions leading to coal bumps include great overburden depth and strong and stiff overlying strata. Rice (1935) stated that the natural condition is one of the key factors associated with coal mine bumps. Prassetyo (2011) found that both the interface friction and the width-to-height (W/H) ratio affect the potential for violent failure of coal specimens. However, little experimental work has been done to investigate how interface friction and the W/H ratio of coal specimens would affect the violence of coal specimen failure.

This paper is divided into two parts. First, the interface friction between the coal specimen and the loading platen is determined. Second, the effect of interface friction and the W/H ratio of coal specimen on the potential for violent failure is studied.

2. Determination of interface friction

The direct shear test was used to determine the interface friction between coal specimen end surfaces and loading platen using the GCTS Rock Direct Shear System RDS-200. Two types of contacts were examined. The first type of contact was the greased coal and greased steel platen. The second type was direct contact between coal specimen end and steel platen without grease. The Mohr–Coulomb envelopes were constructed from test data obtained under different normal stresses in order to determine the magnitude

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of the interface friction (Fig. 1). It was found that when the end surfaces of coal specimen and the steel platen were lubricated with grease, the interface friction is approximately 0.1, while approximately 0.25 for direct contact without grease.

3. The mode of failure changing with interface friction and W/H ratio

NIOSH MRS (Mine Roof Simulator) has been used to apply load on coal specimens, however a load cell has been used to record the response of coal specimens to the applied load. The mode of failure, violent or non-violent, has been examined for coal specimens having different W/H ratios and interface frictions. All tested coal specimens in this research are from Sunnyside Coal Seam in Utah, USA. The coal specimens have been tested under load control of 320 lb/s (1 lb = 4.45 N). Since the water content would affect the mechanical properties of coal, the coal specimens were dried before testing. The average density for 17 cylindrical coal specimens is approximately 78.2 lb/ft^3 (1 ft = 0.3048 m).

The MRS is the largest active load frame of its kind in the world. It was originally designed and is still being used for testing the structural integrity of longwall shields. It can accommodate specimens up to 4.88 m high, 6.1 m wide and 6.1 m long. The MRS performs precision load testing by closed-loop, servo-controlled actuators with six degrees of freedom control of the lower platen. The MRS can apply up to 13.636 MN of vertical force through the 610 mm stroke of the lower platen. The reason for using the MRS machine for this research was that the ultimate strength of some coal specimens, especially those specimens with large W/H ratio, is so great and exceeds the ultimate capacity of most laboratory testing machine. The W/H ratio for the tested coal specimens ranged from 1 to 10 and the interface frictions were 0.1 and 0.25. Fig. 2 shows a coal specimen loaded by the MRS machine.

Coal specimens were divided into 5 different groups according to their mode of failure, end constraint conditions, and W/H ratio. Table 1 summarizes the test results for the five coal specimen groups.

4. Results and discussion

Detailed analysis of the results of each group is given below.

4.1. Group-1

For group-1, the interface friction was 0.1 and the W/H ratio ranged from 1 to 3.8. The failure of coal specimens in group-1 was unstable. Once the ultimate strength was reached, sudden loss of strength occurred. It was accompanied by very low acoustic emissions. Debris ejections from the edges of the coal samples were few and at low speed, such that the failure of the coal specimen in group-1 was not recognized until the machine stopped automatically.

Fig. 3 shows an example of crushing failure for coal specimen #13 in group-1. It had a cross-sectional dimension of 132.1 mm × 142.2 mm and a height of 132.1 mm, making the W/H ratio approximately 1. Since the coal specimen had a small W/H ratio and a low end confinement, it was crushed out completely (without core) after testing. The debris sizes for the rib and core zones were similar.

Fig. 4 shows an example of squeezing failure for coal specimen #17 in group-1. It had a cross-sectional dimension of 200.7 mm × 213.4 mm and a height of 71 mm, making the W/H ratio approximately 3.3. Unlike coal specimen #13, the core of which was crushed and destroyed, the core of specimen #17, as shown in Fig. 4, was squeezed and expanded laterally, while the ribs were crushed. Neither splitting nor fault planes were observed in the core of the failed specimen. However, it was disintegrated and damaged probably by shear failure. In other words, the structural integrity of the core was lost after testing.

Therefore, under the same interface friction, the W/H ratio affects the shape of deformed specimen either by crushing or by squeezing. For coal specimens or coal pillars, there are two sources of end confinement. The first one is the W/H ratio and the second one is the interface friction between the machine platens and the coal specimen. For specimen #13, both the interface friction and the W/H ratio were small—this was why it was crushed completely upon failure. While for coal specimen #17, the interface friction was low, but the W/H ratio was relatively high when compared with that of specimen #13. This was why specimen #17 was squeezed and expanded upon failure.

Fig. 5 shows the stress–strain curves obtained from 3 coal specimens in group-1. The other coal specimens in group-1 exhibited the same behavior. It is obvious that the mode of failure is characterized by brittle failure with strain softening. A sudden loss of strength occurs and the strength decreases with increasing strain until the residual strength is reached.

Therefore, a low interface friction between coal specimens and machine platens does not prevent sudden failure when W/H ratio of coal specimens is as small as that shown in group-1. However it reduces the degree of violence in terms of noise and ejection, i.e. low noise pitch and low debris ejections at failure. Coal specimens in group-1 were either crushed or squeezed depending on the W/H ratio.

4.2. Group-2

For group-2, the interface friction was 0.1 and the W/H ratio ranged from 4.7 to 6.5. Deformations of the specimens became more ductile than those in group-1, because the coal specimens could sustain more permanent deformation without sudden loss in load carrying capacity. On the contrary, for group-1, brittle failure took place with no or very little plastic strain.

Fig. 6 shows the stress–strain curve for coal specimen #30 in group-2. It had a cross-sectional dimension of 144.8 mm × 142.2 mm and a height of 27.9 mm, making the W/H ratio = 4.7. The difference in the mode of failure between coal specimens in group-1 and group-2 can be recognized by comparing Figs. 5 and 6. Point *A* in Fig. 6 represents the elastic limit which is the beginning of the plastic strain, while point *B* represents the fracture limit. The plastic strain sustained is more than 3 times the elastic strain. The other coal specimens in group-2 exhibited similar behavior.

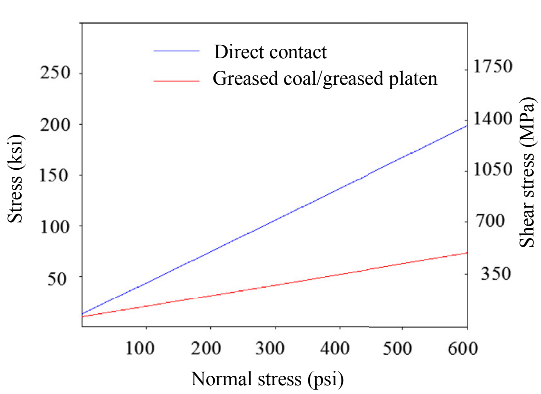

Fig. 1. Mohr–Coulomb envelopes for interface friction between coal specimens and loading platens (1 ksi = 10^3 psi = 6.895 MPa).