Full length article

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

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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 (Pepelakis, 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.
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/ft³ (1 ft³ = 0.3048 m³).

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.
Therefore, for interface friction of 0.1, brittle—ductile transition occurred when the W/H ratio changed from group-1 to group-2. In general, the coal specimens remained brittle when the W/H ratio was less than or equal to 3.8. On the other hand, when the W/H ratio ranged from 4.7 to 6.5, the coal specimens remained ductile under which the coal specimen could sustain further permanent deformation without sudden failure.

Fig. 7 shows a representative example for a coal specimen, i.e. specimen #30 in group-2. The failed coal specimen experienced uniform stress distribution, because the damage was almost the same everywhere through the coal specimen except near the corners that suffered more damage. The grease on the top and the bottom surfaces of coal specimen helped both the edges and the center to deform laterally with almost the same magnitude. Similar modes of failure were found for the other coal specimens in group-2.

4.3. Group-3

For group-3, the interface friction was 0.1 and the W/H ratio was more than 6.7. The failure of coal specimens in group-3 was very stable, i.e. it was neither sudden nor violent failure. The debris ejections and the noise were very low. Moreover, no loss of strength occurred. Coal specimens in group-3 were squeezed and expanded laterally such that their final cross-sectional areas were obviously larger than their initial ones. All tests were stopped at an ultimate load of 2891 kN or more than 138 MPa. It was believed that increasing the load to more than 2891 kN will not change the mode of failure to a stable non-sudden, non-violent failure. Although the core zone of failed coal specimen looked intact, it was highly damaged and broken easily during handling and transporting after testing.

The typical loading—unloading stress—strain curve for a coal specimen in group-3 is shown in Fig. 9. It is divided into 3 segments. The first segment from 0 to point A represents a linear relationship between the stress and strain. The second segment from point A to B represents a linear strain hardening, while the third segment from point B to C represents a parabolic strain hardening. Probably there is a considerable increase in the cross-sectional area of the coal specimen in the third segment due to expansion and squeezing. In Fig. 9, stress calculation was conducted based on the original cross-sectional area of the coal specimen. This

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<td>Mode of failure associated with coal specimens of different W/H ratios and end constraint conditions.</td>
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<td>Group</td>
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was why the third segment of the stress–strain curve was characterized by a parabolic strain hardening.

As shown in Fig. 9, the elastic energy is smaller than the dissipated energy. Hence the burst index defined as the ratio of the strain energy retained (the elastic energy) to the strain energy dissipated (the plastic energy) would be smaller than 1.0, which means that the coal specimen is very unlikely to bump. This demonstrates that coal specimens of W/H ratio = 6.7 or more and interface friction of 0.1 would experience smooth failure, where the elastic energy stored in the core was released smoothly. The burst index is determined from the elastic hysteresis loop in the uniaxial compression loading and unloading tests on rock specimens up to approximately 80% of the compressive strength. Please note how high the strain is, which indicates that the coal specimen is being pulverized.

Gu and Ozbay (2014) used distinct element modeling to investigate the unstable failures in underground mining conditions. They found that when the interfaces experience a stable slip failure, coal side walls are more likely to fail in a stable manner. With occurrence of unstable slips at interfaces, unstable compressive failures are triggered.

In this research, it was found that at a specific combination of W/H ratio and interface friction, the failure becomes stable. So the

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Fig. 3. Coal specimen #13 in group-1 of W/H ratio of 1 before and after failure.

Fig. 4. Coal specimen #17 in group-1 with W/H ratio of 3.3 before and after failure.
stable failure along the interface is a function of both interface friction and W/H ratio. A stable slip failure at the interface prompted the coal specimen to fail smoothly and gradually. Therefore, the elastic energy stored in the core was deactivated gradually as the core deteriorated gradually with increasing vertical load. Hence according to the test results in this research, a coal specimen as small interface friction of 0.1 and W/H ratio of 6.8 or greater is expected to fail neither suddenly nor violently, because this combination of interface friction and W/H ratio allows the interface to fail smoothly and gradually, not suddenly, resulting in no sudden loss of load carrying capacity for the coal specimens.

4.4. Group-4

For group-4, the W/H ratio of coal specimens ranged from 1.2 to 3.6 and the interface friction was 0.25. Two coal specimens out of 13 failed suddenly but not violently with low noise and debris ejections. Conversely, the remaining 11 coal specimens failed very violently with high debris ejection and high pitch noise. In general, the failure of coal specimens in group-4 was more violent in terms of noise and debris ejection than those in the previous three groups. The two coal specimens in group-4 which did not fail violently, i.e. specimens #1 and #21, had the lowest UCS (uniaxial compressive strength) values among the 13 tested coal specimens in that group. Moreover, specimen #21 had the lowest Young's modulus. The elastic energy stored in a uniaxially loaded coal specimen is directly proportional to the square of the UCS (Obert and Duvall, 1967), which means the potential for violent failure increases with increasing UCS. Specimen #1 did not have any visible cracks, while specimen #21 had a crack at its center, but it did not affect the structural integrity of specimen #21.

Fig. 10 shows the variation of UCS and Young’s modulus for coal specimens of the same range of W/H ratio but different interface frictions. To be specific, the comparison includes coal specimens in group-1 and group-4, where the W/H ratio ranges from 1.2 to 3.6 while the interface frictions are 0.1 and 0.25 for group-1 and group-4, respectively. It is obvious that the interface friction has a significant influence on UCS and Young’s modulus of the coal specimens. Fig. 10 also shows that both UCS and Young’s modulus decrease with decreasing interface friction. Hence increasing the interface friction provides the coal specimen with supplemental strength.

In Fig. 10, the two data points inside the ellipse are for specimens #1 and #21 which did not fail violently, unlike the other coal specimens in group-4. These two coal specimens have the minimum UCS among coal specimens in group-4 with interface friction of 0.25. Moreover, their UCS values are very close to the coal specimens in group-1 with interface friction of 0.1. Probably this gives an indication that exceptionally low strength coal pillar would not fail violently in terms of noise and ejection.

Holland (1958) hypothesized that a sudden reduction in interface friction would cause bumps. Assuming for the sake of explanation that the initial interface friction between the coal specimen and the machine platens is 0.25, the UCS of a coal specimen with W/H ratio of 1–3.8 would be one of the red triangles shown in Fig. 10a. At a specific W/H ratio, for instance 3 or 3.6, assuming further that the initial interface friction is suddenly changed from 0.25 to 0.1, the UCS would suddenly decrease from the levels of red triangles to those of the blue diamonds as shown by the vertical black arrows in Fig. 10a, and the coal specimen or coal pillar may fail violently. Hence the failure of interface contact will trigger the compressive failure of a coal specimen. Therefore coal bumps could be avoided when a proper combination of interface friction and W/H ratio exists.

Fig. 11 shows an example of crushing failure for specimens #14 in group-4 that failed violently where the noise pitch and the debris ejections from the ribs were high. It had a cross-sectional dimension of 147.3 mm × 154.9 mm and a height of 121.9 mm with W/H ratio of 1.2. It was crushed completely without core upon failure.

Fig. 12 shows specimen #15 in group-4. It had a cross-sectional dimension of 221 mm × 218.4 mm and a height of 61 mm with W/H ratio of 3.6. It was loaded to its ultimate strength. Once the peak strength was reached, the load was released and the coal specimen was examined. Very little damage occurred in the ribs of the coal specimen even after the applied load had reached its ultimate strength. It is thus structurally intact (Fig. 12). This coal specimen was expected to fail violently if the load was not removed, because the elastic energy stored in it was almost 3 times the dissipated energy as shown in Fig. 13.

After complete unloading, specimen #15 was reloaded again till failure. The failure during the reloading stage was sudden and very violent in terms of noise and debris ejections. Examination of the failed specimen showed that the core was not intact, but highly deteriorated. However, the ribs were completely damaged as shown in Fig. 14.

Fig. 15 shows the loading—reloading stress—strain curves for coal specimen #15. It is obvious that its ultimate strength in the first stage of loading was higher than that of the reloading stage, as it was expected that some micro-cracks would initiate and grow during the first loading stage. Fracture initiation is manifested by departure from the linearity of stress—strain curve near the ultimate strength. However, these cracks did not propagate sufficiently to cause complete failure of the specimen because the load was
released once the ultimate strength was reached. Moreover, the specimen ribs were slightly deteriorated after the first loading as shown in Fig. 12. Hence the confinement from the edges and ribs in the reloading stage would be smaller than those in the first stage of loading. Therefore, the ultimate strength of the specimen in the reloading stage was smaller than that in the loading stage.

In summary, all coal specimens in group-4 with interface friction of 0.25 and W/H ratio of 1.2–3.6 failed suddenly and violently except two specimens whose failure was sudden, but not violent in terms of noise and debris ejection. These two coal specimens had exceptionally low UCS.

4.5. Group-5

For group-5, the W/H ratio of coal specimens ranged from 4.8 to 8.5 and the interface friction was 0.25. The test results from this group showed that when the W/H ratio of specimen was equal to or greater than 7.7, the mode of failure changed from unstable, sudden and violent to stable strain hardening mode. Hence, W/H = 7.7 was considered to be the critical transition factor from violent to non-violent failure, and vice versa. Generally, all coal specimens with W/H < 7.7 failed violently with very high debris ejection and noise once they reached their ultimate strength. Although no acoustic emission data were recorded during testing, it was observed that high strength coal specimens failed more violently than low strength ones did.
Two zones can be recognized on the top surface of the failed coal specimen, rib zone and core zone. In general, the rib zone is damaged completely, because the coal particles in the rib zone are disconnected and separated from each other. The core zone is highly damaged; it would break if it was not handled with extreme care after testing. It was also found that the size of core zone increases with increasing W/H ratio. Rashed and Peng (2013) found that the energy stored in the core zone is the main cause for violent failure of coal specimens.

Fig. 16 shows an example of the results of unstable, sudden and violent failure for coal specimen in group-5. Specimen #33 had a cross-sectional dimension of 132.1 mm × 134.6 mm and a height of 25.4 mm with W/H ratio of 5.3. The rib zone was damaged completely and separated from the core zone of 101.6 mm × 101.6 mm.

On the other hand, coal specimens with W/H ratio of 7.7 or larger did not fail violently. The load was released once it reached 2891 kN which is equivalent to a state of stress of more than 118.6 MPa.
Fig. 17a and b shows representative examples of stress—strain curves for coal specimens in group-5, the failures of which were stable, non-violent and unstable, violent, respectively. As shown in Fig. 17a, there was a clear reduction in stiffness after point A, indicating that the coal specimens had been damaged. This was substantiated by the specimens being easily split apart during handling and transporting after testing. The strain energy stored in the specimens was released in the deterioration process during the strain hardening stage. After the load was released once it reached 2891 kN or a stress of 118.6 MPa, the dissipated energy was much more than the elastic energy stored in the coal specimens. Hence the burst index would be small, thereby very unlikely to bump. Moreover, as shown in Fig. 17a at 118.6 MPa, specimens #14, #4 and #8 were subjected to strains of 40%, 40% and 52%, respectively. The high strains indicated that they had experienced compaction and pulverization due to the applied load, and that increasing the load on these specimens would not change their mode of failure, but would be more pulverized. Please note that the strain at the maximum load shown in Fig. 17a for the three coal specimens that did not fail violently was more than 10 times that shown in Fig. 15 for a coal specimen that failed violently. As shown in Fig. 17b, coal specimens of W/H ratio less than 7.7 failed instantaneously with sudden reduction in strength once the ultimate strength was reached. The failure of these coal specimens was very violent in terms of noise and ejections.

Therefore, the test results showed that under static loading condition, when the interface friction between the loading platens and the coal specimen is equal to 0.25 and the W/H ratio of the coal specimen or the pillar is larger than 7.7, no bump would occur. Consequently it was proposed that no static load would cause violent failure of pillars with interface friction of 0.25 or less and W/H ratio of 7.7 or more. If a pillar of the former characteristics fails violently, it would not be due to a static load, but a dynamic load including an impact load applied in combination with the static load. At higher interface frictions, however, it is expected that the threshold W/H ratio at which the mode of failure would change from violent to non-violent would increase from 7.7 to a higher value.

Rice (1935, 1936) proposed two types of bumps, the pressure bumps and the shock bumps. According to Rice, the pressure bumps occur when a strong and brittle pillar is stressed beyond its strength. The test results contradict this idea, because it was found that coal specimen of W/H ratio of 7.7 or more and interface friction of 0.25 will never fail. Hence the shock bump is more likely to be the main cause for coal mine bumps. A clue that supports this idea is that the bump-prone coal seams are always overlain by a strong and stiff stratum or strata such as limestone, sandstone, or massive shale (Peng, 2008).

5. Conclusions

The violent failure of coal specimen depends on both the interface friction and W/H ratio. Therefore, with a proper combination of W/H ratio and interface friction, the mode of failure can be controlled and converted from violent to non-violent. Consequently, every interface friction is associated with a specific threshold W/H ratio above which the mode of failure is stable and
smooth, and below which the failure would be either sudden, violent or sudden, non-violent. The main conclusions of this paper can be summarized as follows:

(1) When the interface friction between coal pillar/roof and floor is 0.1 and the W/H ratio ranges from 1 to 3.8, the expected mode of failure is sudden brittle failure, but not violent in terms of noise and ejection. So even a very low interface friction does not prevent the sudden failure.

(2) When the interface of friction is 0.1 and the W/H ratio ranges from 4.7 to 6.5, the mode of failure changes from brittle to ductile failure with clear plastic strain and permanent deformation. However, the mode of failure is strain softening.

(3) When the interface friction is 0.1 and the W/H ratio ranges from 6.8 to 10, failure is very stable with strain hardening. Coal specimens expand and are squeezed with very low noise and ejection. This combination of interface friction causes stable slip along the interface and eventually smooth failure.

(4) When the interface friction is 0.25 and W/H ratio is less than 7.7, failure is sudden and violent. The intensity of violence increases with increasing UCS. W/H ratio = 7.7 is the threshold limit between violent and non-violent failures. Stable slip along the interface occurs when W/H ratio = 7.7 and interface
friction = 0.25. Hence every interface friction is associated with a specific W/H ratio to generate stable slip along the interface and eventually smooth failure.

(5) It is expected that under static loading conditions and at specific interface friction, there is a specific W/H ratio above which no bump would occur. In this case, bumps, if occur, belong more likely to the shock bumps as defined by Rice (1935).

Therefore, based on this research, bumps would occur only when the interface friction is 0.25 and W/H ratio is less than 7.7, any other combinations of W/H ratio and interface friction higher than 0.25 remain to be determined.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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