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The influence of interface friction and w/h ratio on the violence of coal specimen failure

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**THE INFLUENCE OF INTERFACE FRICTION AND W/H RATIO ON THE
VIOLENCE OF COAL SPECIMEN FAILURE**

Simon H. Prasetyo

**Thesis submitted to the College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
Mining Engineering**

Approved by

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**Morgantown, West Virginia
2011**

**Keywords: Coal specimen, violent failure, interface friction, w/h ratio, coal mine bumps, core
zone, confinement**

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ABSTRACT

THE INFLUENCE OF INTERFACE FRICTON AND W/H RATIO ON THE VIOLENCE OF COAL SPECIMEN FAILURE

Simon H. Prasetyo

Violent failures of coal pillars, known in practice as coal mine bumps, have long been a subject of investigation. Many field investigations have considered geological conditions that create high stress in the pillar as the main causative factor leading to bumps. In recent years, stress and constraint have been shown to be necessary in producing coal burst.

This research investigated the influence of interface friction and w/h ratio on the violence of coal specimen failure. In satisfying this objective, three violent failure parameters such as peak SPL, core zone failure, and ultimate stress were used to assess the violence of failure. The degree of the violence were investigated at three different interface frictions (high: $\mu = 0.40$, medium: $\mu = 0.22$, and low: $\mu = 0.13$) and six w/h ratios (w/h = 3, 4, 6, 8, 12, and 16). The specimens were axially loaded in a universal testing machine equipped with a microphone to record sound pressure waves for peak SPL calculation. The failed specimens were also photographed after the failure for the measurement of core zones.

The violence of coal specimen failure was found to decrease with increasing w/h ratio and decreasing interface friction. In terms of peak SPL and ultimate stress, the influence of interface friction in reducing the violence was more significant for coal specimens at high w/h ratios than it was at low w/h ratios.

The high peak SPL region ≥ 124 dB was shown to be the most reliable parameter for assessing the violence of coal specimen failure, while the application of core zone failure depends on w/h ratio. Violent failure was also found to be independent of high ultimate stress. Stress merely contributes to the failure of the specimen, but it is the interface friction that greatly influences the degree of the violence.

There are four friction zones on the top end-surface of a coal specimen that may indicate the variation of confinement within the specimen. By the increase of w/h ratio, the zone of confinement was found to increase. Moreover, at the same interface friction, the increase of the confinement may also reduce the violence of failure.

Keywords: Coal specimen, violent failure, interface friction, w/h ratio, coal mine bumps, core zone, confinement

DEDICATION

to

*My father, R. Suyanto
my mother, Herlina Tutirah
and my brother, Ruly F. Satrio*

who gave me strong roots and the courage of my convictions.

*Without their prayers, patience, understanding, support, and most of all love, the completion of
this thesis would not have been possible.*

to

*My fiancé, Bintang, P.E. Siregar
who has been patiently keeping the love between us during the last few years in distance.
I also cherish you for your great contribution in bringing me closer to Him.*

*I may not be able to teach you everything,
but you may learn from how I do things (Syd S. Peng).*

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CHAPTER 1

INTRODUCTION

1.1 Background

Throughout the past century, violent failures of coal pillars, known in practice as coal mine bumps, have often presented dangers to underground coal miners in the U.S. For example, when coal mine bumps happen, coal fragments from the pillar are blasted into the mine entry, mine equipment, standing supports, or both may be damaged or destroyed, harmful gas and dust may be released, and mine personnel may be injured or even killed (Rice, 1935).

Extensive field investigations on coal mine bumps have been conducted in an attempt to explain why coal pillars failed in such violent fashion. However, most of these investigators have considered geological conditions such as strong immediate roof and floor, strong coal, and overburden depth as the main causative factors leading to the bumps. However, it is not clear to what degree geological conditions contribute to this phenomenon.

In fact, experimental work in finding factors contributing to bumps, especially in specialized areas such as the effect of interface friction and width-to-height (w/h) ratio of coal specimens, has attracted less attention among ground control researchers, and little has been written about these effects on the violence of coal specimen failure. Hence, little is known about the degree to which interface friction and w/h ratio may contribute to coal mine bumps.

1.2 Statement of the Problem

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, with shattered coal piling up to the roof line; these bursts are accompanied by audible noises (Peng, 2008, pp. 273, 422). Because understanding the causes of coal mine bumps is essential to

creating a safe underground working environment, this phenomenon has motivated many ground control researchers to conduct extensive field investigations throughout the past century. Most of these investigators have agreed unanimously that specific geological conditions to which the coal seams were subjected are the main factor leading to bumps. These specific conditions include strong and rigid immediate rock strata, strong coal, and great overburden depth (Campoli et al., 1987; Holland & Thomas, 1954; Rice, 1935). More recently, however, Iannacchione and Zelanko (1995) found that no single factor was responsible for coal mine bumps; instead, a combination of geology, stress, and mining conditions influenced the likelihood of pillars to bump.

Certain geological conditions may be essential in producing bumps, but they may not be completely necessary in order for the bumps to occur. For example, bumps have been reported when mining under a weak roof such as siltstone or mudstone (Peng, 2008), at low coal strength of 1,523-2,140 psi (Brauner, 1994; Holland & Thomas, 1954), and at a shallow depth of 500 feet (Holland & Thomas, 1954). Therefore, it seems that geology may be merely a local issue and may not be able to represent the causes of coal mine bumps in general; in other words, certain geological conditions might only be present in the specific mines investigated.

On the other hand, coal pillar failure, whether it is violent or not, occurs mainly because the load applied to the pillar is beyond the pillar strength. In experiments, the strength of coal specimens is greatly influenced by the friction between specimen and machine platens (Babcock, 1985; Khair, 1968; Meikle & Holland, 1965) and specimen size (Daniels & Moore, 1907; Griffith & Conner, 1912; Lawall & Holland, 1937; Pariseau et al, 1977). Unfortunately, in their connection to bump phenomenon, very little has been done, especially in the laboratory setting.

Therefore, a question may be raised: Do interface friction and w/h ratio of coal pillars contribute to the occurrence of coal mine bumps? So far, there have been few explanations for this question in the literature. Only Holland (1958), Meikle and Holland (1965), and Babcock and Bickel

(1984) attempted to discover the necessity of constraints in generating pillar burst¹. This poor understanding necessitates a study of interface friction and w/h ratio in a laboratory setting. It seems that these two aspects deserve close attention in explaining the occurrence of coal mine bump, at least in an experimental way.

The current research was conducted in a laboratory setting in an attempt to discover the influence of these two aspects on the violence of coal specimen failure. Three violent failure parameters such as sound pressure level when the specimen failed, core zone failure, and ultimate stress were examined to assess the likelihood of coal specimens to fail violently.

1.3 Research Objectives

The main goal of this thesis was to investigate the influence of interface friction and w/h ratio on the violence of coal specimen failure by means of unconfined compressive strength (UCS) tests. However, there has been no standard to assess the violence of coal specimen failure. Therefore, the following three violent failure parameters were proposed and investigated:

1. Peak sound pressure level (SPL)
 - Measured peak sound pressures and calculated peak SPLs of the failed specimens;
 - Investigated how the trend of peak SPL would behave with the change in interface friction and w/h ratio;
 - Investigated how the trend of peak SPL could be correlated with the violence of specimen failure.
 - Determined at what peak SPL that a coal specimen could be considered to fail violently.
2. Core zone failure
 - Measured the area of core zone that was left after the specimens failed;

¹ The terms “burst” and “bump” will be used interchangeably. They refer to the same phenomenon, which is the violent failure of coal pillars.

- Investigated the development of the core zone and correlated it with the violent failure of the specimens;
 - Investigated if core zone failure was the necessary condition to produce violent failure of the coal specimen.
3. Ultimate stresses
- Investigated the trend of ultimate stresses with the change in interface friction and w/h ratio;
 - Investigated how the specimens' behavior after reaching their peak strength would change if interface friction and w/h ratio were changed;
 - Investigated how ultimate stresses could be correlated to the violence of specimen failure;
 - Determined at what value of stress a coal specimen could be considered to fail violently.

1.4 Research Hypotheses

It was hypothesized that the violence of coal specimen failure would be influenced by interface friction and w/h ratio. Evidence regarding this hypothesis was obtained by inspecting the applicability of the violent failure parameters to show the following indications at failure:

1. High peak SPL

The basis for this parameter is that coal mine bumps are always accompanied by a high level of audible noises (Peng, 2008).

2. Core zone failure

The basis for this parameter is that coal mine bumps may occur when the core zone fails (Morsy, 2003).

3. High ultimate stress

The basis for this parameter is that coal mine bumps have been considered to be associated with geological conditions such as great overburden depth, strong coal, and strong immediate roof and floor that subject the pillars to a high-stress condition.

1.5 Research Methodology

To test the hypotheses, extensive experiments on coal specimen failure were performed in the laboratory. Coal specimens were obtained from a non-bump prone mine in West Virginia. These specimens were cut into 3 x 3 inch cubes and then prepared to establish the predetermined w/h ratios of 3, 4, 6, 8, 12, and 16. The specimens were then loaded axially into a universal testing machine at different interface friction: high friction, ($\mu = 0.40$), medium friction ($\mu = 0.22$), and low friction ($\mu = 0.13$).

Sound pressures were measured during each test. After the failure of each specimen, the peak sound pressure was measured and peak SPL was calculated. The failed specimen was photographed for core zone analysis. Violent failure parameters were then analyzed for different interface friction and w/h ratio. Conclusions and recommendations were made according to the analysis.

1.6 Scope and Limitation of the Research

This research was conducted on coal specimens with predetermined interface frictions and w/h ratios. Analyses, conclusions, and recommendations were made based on the trends observed within the scope of the interface friction and w/h ratio used in this research.

It was difficult to measure the friction between specimens and loading platens for each specimen before testing, so it was necessary to assume that the interface friction over the specimens

was the same as the interface friction that had been measured in the preliminary tests (see Section 3.3, Preliminary Tests, p. 24), depending on which interface contact was used.

Specimens were prepared with different w/h ratios. The width of each specimen was fixed to 3.0 inches and the height was then adjusted to reach the desired w/h ratio. Other methods to establish w/h ratio such as fixing the specimen height and later adjusting its width or fixing the width to different dimensions other than 3.0 inches were not used. However, as these methods will result in the same w/h ratio, one can predict that the results of this research may also apply for those specimens.

Axial load applied to each coal specimen was stopped at 145,000 lbf (approximately 16,000 psi) to avoid the failure of sandstone platens. Therefore, the violence of coal specimen failure was assessed only within the stress level of 16,000 psi.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The following literature review will offer support for the hypothesis that interface friction and w/h ratio would influence the violence of coal specimen failure. Literature on the coal mine bump phenomenon as a part of coal pillar failure is introduced and field investigations that tried to correlate the bumps with the existence of specific geological conditions are described. The focus of the review is narrowed down to cover previous studies on the influence of interface friction. The review concludes with a proposal of the violent failure parameters which will be used to analyze the influence of interface friction and w/h ratio on the violence of specimen failure.

2.2 Coal Pillar Failures

Failure is a response of a material that is unable to withstand a load that is applied beyond its ultimate strength. A coal pillar is designed to support the overburden and protect the adjacent entries/crosscuts of a mine. Therefore, failure of a coal pillar means the inability of the pillar to serve its designated functions (Peng, 2008, p. 269). It fails when the applied axial stress exceeds its ultimate strength.

Depending on the geological condition and mechanical properties of the coal, coal pillars may fail gradually or violently (Haramy & McDonnell, 1988; Holland, 1958; Holland & Thomas, 1954). When coal pillars fail gradually, they deform axially and laterally in response to the load applied to them during their service life; the deformation may be noticeable. Examples of gradual failure of coal pillars include rib spalling or rib sloughing, which is mainly due to lateral expansion of pillars and orientation of entries/crosscuts with respect to the cleat system within the pillars (Peng, 2008, p. 270).

Violent failures are more instantaneous in terms of stress changes (Maleki, 1995), are usually unpredictable, and occur without any preliminary warning (Rice, 1935). A violent event may also involve a pillar or pillars or a block of coal, resulting in a section, the whole pillar, or the solid block of coal being blasted into an open entry, with shattered coal stacking up to the roof line, accompanied by high intensity of audible noises (Peng, 2008, p. 273). These violent failures of coal pillars are in practice known as coal mine bumps.

Coal mine bumps have been a haunting danger to underground coal miners in the U.S. since the first recorded occurrence in an eastern Kentucky coal field in 1923 (Rice, 1935). The fatalities and injuries to mining personnel and equipment damage they cause mark them as major hazards (Haramy & McDonnel, 1988). They are the most difficult and longstanding engineering problem associated with coal mining in the U.S. (Iannacchione & Zelanko, 1995).

Several field investigations have been conducted since 1935 to study the causes of bumps. Investigators have agreed unanimously to assign a definite set of natural conditions of geology as the causative factors leading to coal mine bumps, though these geological factors may not completely explain why they occur.

2.3 Correlation of Specific Geology Conditions in Generating Coal Mine Bumps

Investigators have tried to correlate strong and stiff overlying strata, coal strength, and overburden depth as a definite set of natural conditions leading to violent pillar failures. However, as demonstrated below, other investigations have shown that the existence of these factors may not always produce pillar failures in such catastrophic manner (Iannacchione & Zelanko, 1995; Peng, 2008). Likewise, their presence cannot always be indicators of a violent failure.

Field investigation of the coal mine bump phenomenon began with Rice (1935), who examined various coal mines of the Cumberland field in Harlan County, Kentucky, and Wise County, Virginia. This investigation was triggered by a series of coal mine bumps that caused many

deaths and injuries and which had been increasing in frequency during the preceding few years. In his report to the U.S. Bureau of Mines, Rice classified the bumps into two types based on the source of load transfer: pressure bump, which was caused by the load on the pillar being greater than its bearing strength, and shock bump, which was caused by a violent rupture of a massive stratum in the overburden, transferring a shockwave to strike one or more of the supporting pillars below. These two types of bumps were later illustrated by Holland (1955) as shown in Figure 2.1.

Figure 2.1. Illustration of pressure and shock bump (Holland, 1955).

As a part of his report, Rice (1935) also mentioned two major conditions favoring the development of bumps: natural conditions and faulty mining methods. Natural conditions included strong and rigid rock strata, structurally strong coal, and overburden depths greater than 1,000 feet deep or even less when mining under a steeply rising area. These conditions were unavoidable because they naturally exist in some mines. Faulty mining methods included making pillars too small, leaving projecting pillars in the line of pillar withdrawal, narrowing to points by diagonally

slicing the inby² ends of pillars, and pulling pillars in separate panels rather than taking out room entry pillars on long retreat lines.

Since the publication of Rice's (1935) report, several investigators have concurred that natural conditions were the main factors causing bumps. Campoli et al. (1987) reviewed five cases of coal mine bump problems in the eastern U.S. and concluded that thick overburden and extremely rigid strata immediately above and below the mined coal bed caused the bumps. They also mentioned that the probability of bump occurrence increased when retreat mining was employed because this method concentrated stresses in the area conducive to bumps.

Holland and Thomas (1954) analyzed 117 occurrences of bumps that happened during the preceding 25 years in U.S. coal mines and found that bumps had been reported when the depth of cover was only 500 feet and when strong immediate overlying and underlying strata were present (usually a massive sandstone or a conglomerate). They also suggested that coal strength was not a critical factor in producing bumps as bumps had been reported in coal seams comprising ultimate strength (3-inch cube coal specimens) of as low as 2,140 psi and as high as 4,700 psi. This was also confirmed by Brauner (1994), who stated that heavy bursts have occurred in low to medium strength of coal (1,523-2,147 psi), while fatalities and injuries due to bumps occurred in coal seams, the ultimate strength of which was between 1,100 and 5,862 psi.

However, in connection with the faulty mining methods mentioned by Rice (1935), Holland and Thomas (1954) discovered that about 67.6% of the bumps took place in areas associated with pillar-line points during pillar-recovery operations or adjacent to an area where pillars were being or had been extracted. Thus, excessive loads resulting from the superimposition of abutment areas on pillars were likely contributing to bumps.

Iannacchione and Zelanko (1995) reviewed the lithologic description of mine roofs from 95 bump sites. They found that 86 sites had the presence of sandstone and as many as 30 sites had shale,

² Inby is to direction away from the shaft or mine entrance and therefore toward the working face.

sandy shale, siltstone, or mudstone sandwiched between the sandstone layers in varying thicknesses. They concluded that no single factor was responsible for coal mine bumps. Instead, bumps occurred as a result of complex arrangements of geology, stress, and mining conditions that were interacting to interfere with the orderly dissipation of stress.

Peng (2008) compiled the rock mechanics properties of rock/coal such as uniaxial compressive strength, Young's Modulus, tensile strength, and Poisson's ratio from various bump sites in the U.S. He found that bumps had occurred even though the strong roof and strong floor (i.e. sandstone) were not located directly above and below the burst coal seam. Bumps had occurred where soft immediate roof and floor (i.e. siltstone or mudstone) were present in the mines.

In summary, even though several investigators have agreed unanimously that a definite set of natural conditions account for coal mine bumps (Campoli et al., 1987; Holland & Thomas, 1954; Rice, 1935), Iannacchione and Zelanko (1995) showed that bumps were not caused by a single factor but by complex arrangements of geology, stress, and mining conditions. Moreover, bumps have been also reported when mining under a weak roof such as siltstone or mudstone (Peng, 2008).

Therefore, it seems that geology may serve as a local issue only and may not represent the causes of coal mine bumps in general.

2.4 Previous Studies on Interface Friction in Generating Pillar Bursts

Laboratory experiments have shown that coal specimen strength greatly depends on interface friction between coal specimens and machine platens (Babcock, 1985; Khair, 1968; Meikle & Holland, 1965) and specimen size (Daniels & Moore, 1907; Griffith & Conner, 1912; Lawall & Holland, 1937; Pariseau, Hustrulid, Swanson, & Van Sambeek, 1977). However, little attention has been given to the roles of interface friction and specimen size with regard to coal mine bumps although their contributions have been cited as a possible contributing factor.

Holland (1958) and Meikle and Holland (1965) were probably the first to introduce a hypothetical effect of friction in generating pillar bursts. This was explained for the first time by Holland, while Meikle and Holland merely investigated the effect of friction on the strength of model coal pillars. Nonetheless, both came up with a hypothetical conclusion about the role of sudden loss of friction in generating a pillar burst.

Having analyzed coal mine bumps on pillar lines³ during the previous 25 years, Holland (1958) stated that friction between the coal pillar and the floor and top rock develops frictional forces that resist the expansion of the pillar induced by the overburden load. This mechanism creates a triaxial state of stress which results in strengthening the coal pillar as the pillar is allowed to absorb more axial stress. In addition, the frictional forces will provide constraint to the central part of the pillar and increase with pillar size until a perfect constraint is reached. As a consequence, there will be a critical size of the pillar at which the frictional forces produce a perfect constraint. When this constraint is suddenly lost by any means, stresses that have been highly developed from the triaxial condition are abruptly released and allow a great expansion of the coal pillar in a severe manner, permitting the violent failure of the pillar to occur.

This concept was strengthened by the observation that brown stains have been commonly seen on the roof at the burst areas. These stains were believed to be an indication of relative motion between the burst-coal pillar and adjacent strata when the friction is being overcome (Holland, 1965). Later on, this finding was confirmed by other researchers who found the same feature at many bump locations; these researchers used several descriptive terms for the phenomenon such as “dusting of red coal” (Iannachione & Zelanko, 1994), “red dust” (Maleki, 1995), “reddish brown coal” (Newman, 2002), and “reddish tint” (Peng, 2007). This feature can be seen in Figure 2.2.

³ Pillar line is an imaginary line separating the extraction pillars and gobs. In this area, two or more abutment loads may be superimposed on the pillars (Holland & Thomas, 1954).

Figure 2.2. Colored staining commonly observed at burst areas (Peng, 2008, p. 437).

Holland (1958) theorized that interface friction between a coal pillar and adjacent strata may contribute to the violent failure of coal pillars. However, since then, very few field investigations or laboratory experiments have been done to prove this concept.

Babcock and Bickel (1984) were the only researchers to extend Holland's hypotheses. They conducted a series of laboratory experiments on coal samples obtained from fifteen mines in eleven coal seams in six states: Alabama, Colorado, Illinois, Pennsylvania, Utah, and West Virginia. In their experiments, 56 pieces of segmented steel platens were used to provide constraint on the top, while Plexiglas was placed on the top of the platen and on the bottom of the coal specimen. The coal specimens were square in shape, 2.13 inch wide and 0.25 inch thick ($w/h = 8.5$).

They predicted that the burst would happen when the constraint was lost through slipping measured at the lower contact interface between coal and Plexiglas. When the burst occurred, a 3,720 in² plate about 3.55 inches below the burst elevation would collect the burst debris and both the vector and horizontal distances the segments were thrown could be recorded. A high-speed camera shooting 350 frames per second was used to record the burst behavior for slow motion study. Then, momentum ($\bar{M}$) and kinetic energy ($K.E.$) were used to characterize the burst using equation 2.1 and 2.2.

$$\bar{M} = \sum_{i=1}^n dm_i \bar{v}_i, \quad (2.1)$$

$$K.E. = \sum_{i=1}^n \frac{dm_i \bar{v}_i^2}{2} \quad (2.2)$$

where dm_i and $\bar{v}_i$ are the mass and velocity of the i -th segment thrown by the burst. The velocity is estimated using equation 2.3.

$$\bar{v}_i = \bar{d}_i \sqrt{g/2h_i} \quad (2.3)$$

where $\bar{d}_i$ and h_i are the horizontal and vertical distances from the burst elevation (3.55 inches), respectively.

The coal samples were then ranked according to their calculated momentum ($\bar{M}$) and kinetic energy ($K.E.$) in order to show their burst proneness (see Table 2.1). Table 2.1 shows an important finding that served as a stimulus for the current research: most of the coal samples were able to produce burst even though the coals were obtained from non-bump prone mines (No. 1 to 9 in Table 2.1).

Based on this result, Babcock and Bickel (1984) believed that most coals can be made to burst if stress and constraint are present. They explained this failure mechanism by a simple modification of the Mohr-Coulomb criterion showing dynamic increases of the Mohr circle as the result of rapid decreases in confinement (see Figure 2.3). The burst will occur when the circle exceeds the static failure envelope.

**Table 2.1 Summary of Test Result and Burst Proneness Rank
(Babcock & Bickel, 1984)**

No	Depth, ft	Mine Number	State	Bursts in Mine	Model Bursts	$K.E.$, in lbf (Rank)	$\bar{M}$, lbs in/s (Rank)
1	200.1	14	PA	No	Yes	1973.5 (5)	829.8 (7)
2	278.8	10	IL	No	Yes	336.3 (11)	307.5 (11)
3	298.5	1	UT	No	Yes	1451.3 (8)	1098.3 (4)
4	298.5	3	CO	No	Yes	610.6 (10)	622.8 (10)
5	298.5	9	CO	No	Yes	2292.0 (3)	641.8 (9)
6	600.2	7	CO	No	Yes	2486.7 (1)	1506.2 (2)
7	829.8	13	WV	No	Yes	8.8 (13)	783.9 (8)
8	898.7	12	WV	No	Yes	2415.9 (2)	56.3 (13)
9	898.7	8	CO	No	Yes	1097.3 (9)	881.7 (6)
10	1,128.3	11	WV	Yes	No	-	-
11	1,400.6	2	UT	Yes	Yes	1893.8 (6)	1019.4 (5)
12	1,649.8	4	CO	No	No	-	-
13	1,774.5	6	CO	Yes	Yes*	1796.5 (7)	1150.2 (3)
14	2,200.9	15	AL	Yes	Yes	8.8 (12)	168.0 (12)
15	2,797.8	5	CO	Yes	Yes	2097.3 (4)	1992.1 (1)

*Weak bursts sometimes occur.

Figure 2.3. Modified Mohr-Coulomb criterion showing the dynamic increase of the Mohr circle as the result of rapid decrease in confinement (Babcock & Bickel, 1984).

Babcock and Bickel (1984) made an important observation, which is that coals can be made to burst if the friction which provides constraint to the specimens is suddenly lost. This finding was one step further than that of Holland (1958), who had first proposed the concept. However, this finding was still limited to one interface friction (between coal specimen and the segmented platen) and one w/h ratio (8.5). This limitation motivated the current research to expand the interface friction value and use diverse w/h ratios of coal specimens.

2.5 The Proposed Violent Failure Parameters

Even though coal in general is likely to produce bump (Babcock & Bickel, 1984), relatively little has been written on how to quantify the bump. In this research, three parameters were used in assessing the likelihood of coal specimens to fail violently:

1. Sound pressure level (SPL)

One may be able to recognize when a coal pillar bumps because the bump is accompanied by audible noises (Peng, 2008, p. 273). But, noise⁴ is a subjective matter. One may only recognize it as a sound of coal pillar failure, while another may recognize it as a pillar bump. Hence, in this research, a parameter is needed to quantify the SPL that results from the failure of a specimen. The specimen would be considered to fail violently if it resulted in a high peak SPL.

When a specimen fails, it causes fluctuation in air pressure. This fluctuation travels through any medium, such as air, in the form of a fluctuating wave (longitudinal wave) and produces sound. The amount of the air pressure fluctuation during its travel is called sound pressure and is expressed in a unit called Pascals (Pa). The human ear can be exposed without pain to sound pressure over a wide range of 0.00002 Pa to 20 Pa within the limited frequencies of 12 Hz – 20,000 Hz.

⁴ Noise: unwanted sound

Due to the broad range of sound pressures, another unit called decibel (dB, or tenth (deci) of a Bell⁵) is used to manage these numbers into a more convenient scale (equation 2.4). The dB scale is obtained by taking a logarithm of the sound pressure relative to a reference value. This logarithmic scale is called sound pressure level (SPL).

$$L_p = 10 \log_{10} \left(\frac{p_{rms}^2}{p_{ref}^2} \right) = 20 \log_{10} \left(\frac{p_{rms}}{p_{ref}} \right) \quad (dB) \quad (2.4)$$

where L_p is SPL, p_{ref} is the reference value of sound pressure ($20 \mu\text{Pa rms}$), and p_{rms} is the root-mean-square sound pressure being measured.

Sound pressures measured in this research were impulsive and discontinuous. Impulsive sound pressure is a sharp rise and rapid decay in sound pressure occurring in a short interval of time, while continuous sound pressure has negligibly small fluctuations of level within the period of observation.

Since there has been no standard in determining at what dB a peak SPL can be considered a high peak SPL in terms of coal specimen failure, the trend of peak SPL at failure at each interface friction and w/h ratio was investigated. The tendency of peak SPL to show violent or non-violent failure was expected. In order to deliver understanding in recognizing the value of each peak SPL at the failure of coal specimen, three impulsive tests were performed by measuring peak sound pressure of normal clapping hands, dropping a claw hammer on concrete floor, and dropping a claw hammer on steel base. Average peak SPL for each test was then calculated. The method of the impulsive tests will be explained in detail in Chapter 3.

⁵ This unit was named after Alexander Graham Bell for his great work as the pioneer of the telephone.

2. Core Zone Failure

Holland and Thomas (1954) proposed a probable stress distribution in a coal pillar located beyond the abutment area by dividing the pillar into three zones according to its stress level (Figure 2.4). These zones are:

1. where the stresses are less than the pre-mining stresses; this zone is located at the pillar edges and the stresses are comparatively low;
2. where the stresses are greater than the pre-mining stresses; the stresses quickly build up to the maximum within a short distance from the pillar edges; and
3. where the stresses are the same as the pre-mining stresses; this zone is located at the pillar center and the stresses gradually drop from maximum to uniform stress.

Figure 2.4. The stress distribution in a coal pillar located beyond the abutment area (Holland & Thomas, 1954).

Morsy (2003) also divided yield pillar into three zones according to their confining level (Figure 2.5). The summary of each zone follows:

1. **Core zone:** This zone occupies the center portion of the pillar and does not experience any plastic deformations as confining stresses are applied. Therefore, the core zone stores a significant amount of elastic strain energy. Once this zone fails, it will release the energy in a violent fashion as a bump. For the purposes of this study, the failure of the core zone is one of the criteria for the failure of coal specimens to be considered violent (second parameter).
2. **Transition zone:** This zone is located between the rib and core and is characterized by a wide range of confining stresses, increasing from outside toward the core. Part of the energy stored in this zone is dissipated in the form of plastic deformation, while a significant amount of elastic strain energy is stored in this zone.
3. **Rib zone:** This zone occupies the pillar corners and ribs. As it is bounded by free space, this zone has low confining pressures. That is why pillar yielding will always start from this zone and extend toward the core zone.

Figure 2.5. The three zones of confinement in a yield pillar (Morsy, 2003).

Lu et al. (2008) investigated the development of elastic core in a pillar (Figure 2.6) and the minimum principal stress (Figure 2.7) with respect to its interface shear strength and w/h ratio. In their model, the percentage of elastic core and the magnitude of minimum principal stress (as the confinement) within the pillar increased with the increase of interface shear strength and w/h ratio. Furthermore, the increase of average minimum principal stress was more significant with the increase of interface shear strength.

Figure 2.6. The development of pillar elastic core with respect to its interface strength and w/h ratio (Lu et al., 2008).

Figure 2.7. The average minimum principal stresses with different w/h ratios and interface properties (Lu et al., 2008).

Among the three authors whose studies are described above, only Morsy (2003) attempted to correlate the failure of core zone with coal mine bump phenomenon even though it was still numerical. Therefore, laboratory experiments are still needed to gain a better understanding of whether the failure of this zone would be able to serve as a parameter in assessing the likelihood of a bump occurring.

3. Ultimate stress

The basis for this parameter is that coal mine bumps have been considered to be associated with geological conditions such as great overburden depth, strong coal, and strong immediate roof and floor that cause the pillars to be subject to high stress conditions. However, as with high peak SPL, there has been no standard in determining the violence of coal specimen failure in terms of high ultimate stress. For this reason, the ultimate stress for each specimen in this study was taken from its stress-strain curve and plotted against w/h ratio at each interface friction. How the importance of high ultimate stress on the violence of the failure would then be discussed.

CHAPTER 3

EXPERIMENTATION

3.1 Introduction

This research was conducted in order to determine whether interface friction and w/h ratio play a significant role in the violence of coal specimen failure. In order to achieve this goal, UCS testing on coal specimens was performed. Specifically, a total of 61 coal specimens were tested at different interface frictions and w/h ratios. During the testing, sound pressures for each specimen tested were recorded and the peak SPL was computed. After the failure of each specimen, photographs of the failed specimen were taken to analyze the appearance of core zones. Ultimate stress was then taken from the stress-strain curve of each failed specimen.

3.2 Specimen Preparation

The experiment was conducted using coal samples obtained from a non-bump prone mine in West Virginia. A non-bump prone mine was selected because the hypotheses of this study were not affected by geology. Taking samples from a bump-prone mine might have been inappropriate for the study because of the possible influence of geology.

Coal samples from the mine were treated using the techniques of cutting and grinding. Figure 3.1 shows the specimen preparation process. After the coal samples were obtained from the mine (Figure 3.1a), they were cut into smaller cubes (3 x 3 inches surface dimension) and all four sides were ground (Figure 3.1b). In order to investigate the influence of w/h ratio, after being ground, the samples were cut along the bedding planes at different intervals (sample thickness) that would result in different w/h ratios. W/h ratios used in this research were 3, 4, 6, 8, 12, and 16. Therefore, the predetermined sample thickness would be 1 in., 0.75 in., 0.5 in., 0.375 in., 0.25 in., and 0.1875 in., respectively (illustrated in Figure 3.1c). The samples were cut slightly larger than the predetermined

thickness to allow the grinding wheel to smooth the sample surfaces without over-grinding (i.e., the height after grinding becomes lower than the predetermined height).

The top and bottom surfaces of these samples were ground to the predetermined height. After being ground, the samples were dried and named according to w/h ratio, type of test, and specimen number. Samples that have been prepared were called specimens; all specimens were photographed.

It has been hypothesized that the violence of coal specimen failure would be influenced by interface friction and w/h ratio. Hence, the preparation of coal specimens into w/h = 3, 4, 6, 8, 12, and 16 sets up the conditions of w/h ratio for testing the hypothesis.

a. Coal samples from the mine ready for cutting and grinding

b. Coal samples after cutting and grinding on all four sides (3 x 3 inch)

c. Illustration of w/h ratio of coal specimens used in this research

Figure 3.1. The coal sample preparation steps.

3.3 Preliminary Tests

3.3.1 Determining the interface friction values

In this research, interface friction values between the specimen surfaces (top and bottom) and loading platen were determined by the mean of direct shear test on the interface contact. The test was performed using the GCTS Rock Direct Shear System RDS-200 (Figure 3.2).

Figure 3.2. The GCTS Rock Direct Shear System RDS-200 with computer-operated system.

The effect of interface friction in this research was investigated using three different interface friction values. Hence, three interface contacts were used for the UCS tests. Each condition was tested to determine the friction value. The testing of each contact is explained below.

1. Contact 1 (coal specimen between sandstone platens)

In order to obtain the interface friction for contact 1, the test arrangements were as follows: a ground, cube-shaped coal sample (2 x 2 x 2 in.) was placed in the upper shear box and encapsulated with bolt-anchor sulfaset cement. A ground cube of sandstone (3 x 3 x 3 in.) was placed in the lower shear box and encapsulated with the same material.

For the shear test, the upper shear box was axially loaded to a certain normal stress and sheared (pulled) at a constant rate of 0.0039 in/s (0.5 mm/s) until the shear distance reached 0.197

inch (5 mm). This test was repeated at different normal stresses (100, 200, 300, 400, and 500 psi). The Mohr-Coulomb envelopes were then constructed to determine the interface friction, which is the tangent of the internal friction angle (θ). Both shear surfaces were re-ground to preserve the original interface contact before the next test.

The interface friction value obtained from testing interface contact 1 was categorized as high friction.

2. Contact 2 (coal specimen between lubricated sandstone platens)

The method to determine the interface friction for contact 2 was the same as that for contact 1, except both the shear surfaces (coal and sandstone) were coated with lubricant in order to reduce the friction.

The interface friction value obtained from testing interface contact 2 was categorized as medium friction.

3. Contact 3 (coal specimen between lubricated steel platens)

The method to determine the interface friction for contact 3 was the same as that for contact 2, except the sandstone platen was replaced by a lubricated steel platen 7 inches in diameter. The use of this platen was intended to reduce the friction even more than in contact 2.

The interface friction value obtained from testing interface Contact 3 was categorized as low friction.

3.3.2 Strength properties of sandstone platens and coal sample

To determine the strength properties of the sandstone platen and coal samples used in this study, several sandstone cores 2 inches in diameter were drilled in the laboratory. Similarly, several cubical coal specimens (3 x 3 x 3 inches) were prepared and several coal cores (2 inches in diameter) were also tested. These tests included the UCS test, direct shear test, and Brazilian test (for the sandstone cores only).

3.3.3 Impulsive tests

This test was intended to provide a sense of the SPL that would be calculated from peak sound pressures of coal specimens at failure. Three impulsive tests were done by measuring peak sound pressures from three different sources: clapping hands with normal power, dropping a claw hammer on a concrete floor, and dropping a claw hammer on a 8 x 8 x 2-inch steel base. These sources were chosen as they are simply recognizable.

The impulsive test for measuring peak sound pressures of clapping hands was done by placing a microphone 12 inches away from the source of clapping and at the same height as the source. The microphone was connected to a data acquisition system that was also connected to a computer equipped with Pimento 2.1 software, which enables the computer to read the sound pressures recorded by the microphone and displays them on the computer screen. Ten sets of data were taken. Each set was obtained by generating a normal clapping sound. After the clapping, the recording was stopped and the peak sound pressure was recorded. The second recording began and a normal clapping was generated again. The recording was stopped and the peak sound pressure was again recorded. This test was done until 10 data recordings were gathered.

The same procedures were also applied for the impulsive test of dropping a claw hammer on the concrete floor and dropping a claw hammer on the steel base. Figure 3.3 shows the claw hammer and steel base lying on the concrete floor. The claw hammer was freely dropped from about 3 feet above either the concrete floor or steel base, depending on which impulsive test was being conducted. The microphone was placed 3 feet away from the source of the contact point of the dropped claw hammer and the concrete floor or steel base. Ten sets of data were taken. Each set was obtained by generating a free drop. After the drop, the recording was stopped and the peak sound pressure was recorded. The second recording began and a free drop was done again. The recording was stopped and the peak sound pressure was again recorded. Each test, both dropping the claw hammer on the concrete floor or on the steel base, was done until 10 data recordings were gathered.

Figure 3.3. The claw hammer and steel base used in the impulsive test.

3.4 The Unconfined Compressive Strength (UCS) Test

The UCS test was intended to simulate the loading condition experienced by a coal pillar in an underground mine. In order to obtain the violent failure parameters of the coal specimens, the specimens were axially loaded in an MTS testing machine.

Several sandstone cores were drilled from sandstone blocks in the laboratory. The sandstone cores were 7.5 inches in diameter and 6 inches in height. These cores served as the loading platen to satisfy interface contact 1 and 2. Coal specimens at $w/h = 3, 4$, and 6 were all strain gauged, but coal specimens at $w/h = 8, 12$, and 16 were not because the specimens' thicknesses were thinner than the gauge length. Hence, for specimens at $w/h = 8, 12$, and 16 , the load-deformation values were obtained from the testing machine and then converted to stress and strain. All the pre-failure slopes of these specimens were then shifted to be approximately equal to the slope of the strain gauged specimens at $w/h = 6$. In the test, each coal specimen was placed between specific upper and lower loading platens, depending on the interface contact used (contact 1: high interface friction, contact 2: medium interface friction, or contact 3: low friction).

A total of 61 coal specimens at three interface conditions and six w/h ratios were tested. During each test, sound pressures were recorded by the same equipment used for the impulsive test. Figure 3.4 shows the arrangement of the UCS test of a coal specimen to obtain its violent failure parameters (in this case, contact 1: high friction).

The rate of loading used was 100 psi/s (0.75 MPa/s), which was within the range of rate of loading recommended by ISRM⁶ (72.5-145 psi/s or 0.5-1.0 MPa/s). Each specimen was axially loaded up to 145,000 lbf in order to avoid sandstone platens failure.

Load control mode⁷ was engaged to perform the test as this mode led to unstable failure of coal specimen once the load applied was beyond the specimen peak strength. Other control mode such as axial or circumferential strain control mode⁸ may be useful for controlling post-failure behavior of the specimen. Therefore, axial or circumferential strain control mode would not have been appropriate for use in this research as coal mine bump, in fact, is an example of unstable behavior of coal pillar failure (MTS Rock and Concrete Mechanics Testing System, 2004).

Figure 3.4. Arrangement of the UCS test of a coal specimen to obtain its violent failure parameters (contact 1: high friction).

⁶ ISRM: International Society for Rock Mechanics

⁷ Load control mode allows the load actuator maintaining the applied load even though the specimen strength has been exceeded. Hence, this mode leads to a sudden complete failure.

⁸ Axial or circumferential control mode provides sensitive means of detecting specimen failure from axial or circumferential displacement, respectively. Under either one of these modes, the loading actuator is retracted to reduce the applied load once the peak strength of the specimen is reached; permitting the deformation rate stabilizes again. Hence, the failure of specimen will be more controllable than that under load control mode.

3.5 Analysis of Violent Failure Parameters

1. Peak sound pressure level (SPL)

Peak SPL for each specimen was calculated using equation 2.4 after subtracting the peak sound pressure from the mean sound pressure (equation 3.1). This calculation was made because during the loading, the microphone would also record the surrounding sound pressures and display the mean of those pressures.

$$L_p = 20 \log_{10} \left(\frac{p_{rms} - p_{mean}}{p_{ref}} \right) \quad (dB) \quad (3.1)$$

where, p_{mean} is the average mean sound pressure.

Peak SPL of specimens at failure was then plotted for each interface friction and w/h ratio. This plot was intended to show whether there was any significant difference in SPL of specimens at failure that may be used to distinguish violent from non-violent failures. In other words, this plot was intended to show the peak SPL that could be considered the high peak SPL that would indicate violent failure of a coal specimen. Once the high peak SPL was established, the other two parameters were inspected to see if they matched each other according to the violence of the specimen's peak SPL. In other words, did the three violent failure parameters support each other?

2. Core zone failure

After each test, the failed specimen was photographed for image analysis. This analysis was performed to measure the core zone that appeared after the failure. Even though some specimens did not fail when the axial load had reached 145,000 lbf, they were still photographed for the analysis. A freeware image processing program called ImageJ (Rasband, July 9, 2007) was used to do the image analysis. In this study, the program was used to calculate the area of core zone based on the different colors that appeared on the top end-surface of the failed specimen.

All the pictures of top end-surface were first edited in Adobe Photoshop Element 4.0 to enhance the color difference before being transferred to ImageJ for calculating the area of the

enhanced zone. The percent area of the enhanced zone for each specimen was plotted for each interface friction and w/h ratio with the intention to inspect the development of the core zone and whether core zone failure would always correspond to high peak SPL.

3. Ultimate stress

As with the core zone, the ultimate stress for each specimen was plotted for each interface friction and w/h ratio with the intention to inspect whether there would be any significant difference in stresses that may be useful to indicate the violence of specimen failure. The plot was also intended to show if high ultimate stresses would correspond to high peak SPL, which may also correspond to violent failure.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introductory Paragraph

According to the hypothesis, interface friction and w/h ratios were expected to contribute to the violence of coal specimen failure. Violence was examined in terms of three violent failure parameters: (1) peak SPL, (2) core zone failure, and (3) ultimate stress. In this chapter, the results of the tests are presented and discussed.

This chapter starts with the results of the preliminary experiments to determine the interface friction values, strength properties of the sandstone platens and coal samples used in this research, and peak SPL from the three impulsive tests. Next, violent failure parameters obtained from the UCS tests of coal specimens at three interface frictions (high, medium, and low) and six w/h ratios (3, 4, 6, 8, 12, and 16) are presented. Based on the results, trends for each parameter are described. A discussion of the applicability of each parameter towards the violence of coal specimen failure is provided. The implications of the results for the coal mine bump phenomenon are also discussed.

4.2 Results of the Preliminary Tests

Interface friction values were determined by means of direct shear tests on the interface contact. Figure 4.1 shows the Mohr-Coulomb envelope for each interface friction contact, and Table 4.1 contains the interface friction values obtained for each contact.

It has been hypothesized that the violence of coal specimen failure would be influenced by interface friction and w/h ratio. Therefore, the results of the preliminary tests on the interface friction contacts set up the conditions of interface friction for testing the hypothesis. Three interface friction values were established according to their type of contact: high friction, $\mu = 0.40$, medium friction, $\mu = 0.22$, and low friction, $\mu = 0.13$.

Figure 4.1. The Mohr-Coulomb envelope for each interface contact
 (* see Table 4.1 for the definition).

Table 4.1 Interface Friction Value for Each Interface Contact

No	Interface contact	Interface friction	Interface friction value ($\tan \theta$)
1	Contact 1 (coal-sandstone)	High	0.40
2	Contact 2 (Coal-lubricated sandstone)	Medium	0.22
3	Contact 3 (Coal-lubricated steel platen)	Low	0.13

Table 4.2 shows the strength properties of the sandstone platen and coal samples used in this research. Strength properties 1 through 4 were averaged from five specimens tested, both for sandstone and coal. Strength properties 5 and 6 were obtained from direct shear tests of six sandstone specimens (three different normal stresses) and 16 coal specimens (five different normal stresses). For analysis purposes, the peak SPL from the three impulsive tests as a part of the preliminary tests is placed in section 4.3.1.

Table 4.2 Mechanical Properties of Sandstone and Coal Sample used in This Research

No	Strength properties	Sandstone	Coal
1	Ultimate strength (UCS), σ_c (psi)	12,698	1,750
2	Young's Modulus, E ($\times 10^6$ psi)	4.8	0.6
3	Poisson's Ratio, ν	0.4	-
4	Tensile strength (Brazilian test), σ_t (psi)	439	-
5	Cohesion (peak), c (psi)	245.9	101.4
6	Friction angle (peak), θ ($^\circ$)	43.8	34.1

4.3 The Effect of Interface Friction and w/h Ratio on Peak Sound Pressure Level

The graph of sound pressure wave for each specimen can be seen in Appendix B. Using equation 2.4, the peak sound pressure for each specimen was converted into peak SPL. The results of the conversion for all tests at each interface friction and w/h ratio are shown in Table 4.3. Each peak SPL is then plotted at each w/h ratio and interface friction. A clear separation of peak SPL region to distinguish which peak SPL shows violent failure (high peak SPL) and non-violent failure (low peak SPL) was expected. Once violent and non-violent failure regions were classified, the other two violent failure parameters were evaluated based on this classification.

Table 4.3 Peak and average SPL at Failure and Ejection during the Loading for Each Specimen at Each w/h Ratio and Interface Friction

Interface friction	Specimen code	At failure				Ejection during loading				
		Each specimen		Average		Each specimen		Average		
		Peak sound pressure (Pa)	Peak SPL (dB)	Peak sound pressure (Pa)	Peak SPL (dB)	Peak sound pressure (Pa)	Peak SPL (dB)	Peak sound pressure (Pa)	Peak SPL (dB)	
High (0.4)	3c-ucs 12	47.2	127.4	182.1	139.2	31.9	124.1	42.4	126.5	
	3c-ucs 8	48.6	127.7			37.4	125.4			
	3c-ucs 16	349.3	144.8			60.4	129.6			
	3c-ucs 3	234.5	141.4			66.6	130.5			
	3c-ucs 9	230.8	141.2			15.9	118.0			
	4c-ucs 8	429.0	146.6	247.8	141.9	120.0	135.6	71.1	131.0	
	4c-ucs 2	301.7	143.6			56.6	129.0			
	4c-ucs 4	177.9	139.0			92.5	133.3			
	4c-ucs 20	82.6	132.3			15.4	117.7			
	6c-ucs 4	143.6	137.1			111.7	134.9			60.0
	6c-ucs 1	41.7	126.4	30.2	123.6					
	6c-ucs 5	149.8	137.5	84.3	132.5					
	8c-ucs 14	83.4	132.4	31.2	123.9					
	8c-ucs 3	71.9	131.1	42.1	126.5					
	8c-ucs 10	67.7	130.6	98.3	133.8	20.8	120.3	34.8	124.8	
	8c-ucs 9	79.1	131.9			59.8	129.5			
	8c-ucs 13	189.8	139.5			19.9	120.0			
	12c-ucs 11	Specimens did not fail	51.5			128.2	44.1			126.9
	12c-ucs 16		38.2			125.6				
	12c-ucs 17		76.9	131.7						
	12c-ucs 5		9.9	113.9						
	16c-ucs 7		45.9	127.2						
	16c-ucs 6		23.1	121.3	34.5	124.7				
	16c-ucs 4		10.8	114.6						
Medium (0.22)	3c-ucs 14		276.1	142.8	113.1	135.0	112.9	135.0	51.9	128.3
	3c-ucs 2		74.9	131.5			31.7	124.0		
	3c-ucs 4		49.9	127.9			38.6	125.7		
	3c-ucs 15	51.5	128.2	24.4			121.7			
	4c-ucs 15	47.3	127.5	27.4			122.7			
	4c-ucs 23	80.1	132.1	58.1	129.3	24.9	121.9	25.1	122.0	
	4c-ucs 14	46.7	127.4			22.9	121.2			
	6c-ucs 8	52.7	128.4			33.3	124.4			
	6c-ucs 2	25.0	122.0	38.9	125.8	21.2	120.5	27.2	122.7	
	8c-ucs 4	14.9	117.4			52.8	128.4			
	8c-ucs 13-1	6.9	110.7			50.2	128.0			51.5
	12c-ucs 11-1	Specimens did not fail	24.0	121.6	25.9	122.3				
	12c-ucs 13		8.6	112.6						
	12c-ucs 12		45.1	127.1						
	16c-ucs 2		14.9	117.5	14.2	117.1				
	16c-ucs 1		13.5	116.6						
Low (0.13)	3c-ucs 5		184.4	139.3	124.8	135.9	26.5	122.4	38.9	125.8
	3c-ucs 6	125.2	135.9	64.8			130.2			
	3c-ucs 18	64.7	130.2	25.4			122.1			
	4c-ucs 22	9.0	113.0	5.8			109.2			
	4c-ucs 1	9.6	113.6	31.0	123.8	16.7	118.4	14.3	117.1	
	4c-ucs 18	19.3	119.7			19.3	119.7			
	4c-ucs 5	77.9	131.8			15.8	118.0			
	4c-ucs 17	39.1	125.8			13.8	116.8			
	6c-ucs 6	61.0	129.7			23.4	121.4			
	6c-ucs 7	141.9	137.0	101.5	134.1	70.1	130.9	46.7	127.4	
	8c-ucs 21	3.9	105.8	10.7	114.6	2.7	102.7	8.8	112.9	
	8c-ucs 5	8.6	112.7			11.8	115.4			
	8c-ucs 19	15.9	118.0			17.4	118.8			
	8c-ucs 16	16.6	118.4			5.9	109.4			
	8c-ucs 17	8.7	112.8			6.1	109.7			
	12c-ucs 7	0.7	91.2	7.8	111.8	2.7	102.5	8.6	112.7	
	12c-ucs 9	7.8	111.8			6.1	109.7			
	12c-ucs 10	21.1	120.5			17.1	118.7			
	12c-ucs 8	1.5	97.4			5.1	108.1			
	16c-ucs 3	Specimens did not fail	16.2			118.2	29.0			123.2
16c-ucs 15	41.8		126.4							

4.3.1 Determination of violent and non-violent failure regions based on peak SPL

As shown in Figure 4.2, peak SPLs of all the specimens at failure are scattered. Groups of high and low peak SPL cannot be clearly determined from this figure, but peak SPLs seem to start showing an indication of separation at 120 dB. The average peak SPLs from Table 4.3 are plotted in Figure 4.3. The plot shows a clear separation of average peak SPLs between 114.6 and 123.8 dB. For this reason, the average peak SPLs in Figure 4.3 were grouped into three regions: above 123.8 dB (the upper boundary of the blue band), between 123.8 and 114.6 dB, and below 114.6 dB (the lower boundary of the blue band).

To strengthen the rationale for classifying the range of high and low peak SPLs, results from three impulsive tests are plotted in Figure 4.4. It can be seen that the average peak SPL for normal clapping, dropping the claw hammer on concrete floor, and dropping the claw hammer on a steel base were 111 dB, 116 dB, and 119 dB, respectively.

Thus, based on the observation shown in Figures 4.2 – 4.4 and gained from the UCS tests, three regions of peak SPL were proposed: high (≥ 124 dB), medium ($124 \text{ dB} < \text{peak SPL} < 114 \text{ dB}$), and low ($\leq 114 \text{ dB}$). The low peak SPL region ($\leq 114 \text{ dB}$) can still be tolerated by the human ear. The medium peak SPL region ($114 \text{ dB} < \text{peak SPL} < 124 \text{ dB}$) may be considered a loud noise because the average peak SPL of dropping the claw hammer on concrete floor (116 dB) and dropping a claw hammer on a steel base (119 dB) are within this range. The high peak SPL region ($\geq 124 \text{ dB}$) can reasonably be considered an excessive noise exposure for the human ear and is equivalent to or louder than the sounds associated with a coal bump. In fact, during the UCS tests, it was observed that pieces of the coal specimens that failed with peak SPL $> 124 \text{ dB}$ were thrown out as if from a small explosion. Therefore, a failure of a coal specimen that produced a peak SPL $\geq 124 \text{ dB}$ was considered a violent failure, and peak SPL $< 124 \text{ dB}$ was considered a non-violent failure.

Figure 4.2. The peak SPL of each specimen at failure (Indication of separation is shown at 120 dB).

Figure 4.3. The average peak SPL at failure (Three regions are indicated: above 123.8 dB, between 123.8 and 114.6 dB, and below 114.6 dB).

Figure 4.4. The peak SPLs of impulsive tests
(Average peak SPL for each impulsive test is indicated by the straight line).

4.3.2 Variation of violence failure based on peak SPL due to interface friction and w/h ratio

For the sake of explanation, the peak and average peak SPLs from Figures 4.2 and 4.3 are re-plotted in Figures 4.5 and 4.6, respectively, with the three regions of peak SPL: high, medium, and low. As the plots of peak and average peak SPLs show the same trend, the results and discussion presented in this chapter will refer to the average peak SPL shown in Figure 4.6.

Figure 4.5. The peak SPL of each specimen at failure with three peak SPL regions
(High, medium, and low peak SPL).

Figure 4.6. The average peak SPLs at failure with three peak SPL regions (High, medium, and low peak SPL).

Variation of the average peak SPL in Figure 4.6 shows a decreasing trend with the increase of w/h ratio and the decrease of interface friction. The average peak SPL at each interface friction varies in similar manners in that it decreases with the increase of w/h ratio. But it shows a much greater reduction from high (red line) to low friction (green line) than from medium (blue line) to low friction (green line). This indicates that in terms of average (or peak) SPL, the violence of coal specimen failure is truly influenced by interface friction and w/h ratio: it decreases with increasing w/h ratio and decreasing interface friction.

In addition, the influence of interface friction on the violence of coal specimen failure is also found to be more significant at high w/h ratio than it is at low w/h ratio. This can be observed in Figure 4.6; regardless of interface frictions, coal specimens are still expected to fail within high peak SPL region up to w/h = 6, but starting from w/h = 8 to 16, only coal specimens at high interface friction are still likely to fail within high peak SPL region while the opposite is found for specimens with medium and low interface friction. As illustrated in Figure 4.6, if the trend line for high interface friction (red line) is extended to w/h = 16 (the red dashed line), the line may still be in the high peak SPL region (i.e., inside the blue band) which indicates the proneness of specimens to fail

violently. Yet the opposite may be found for medium and low interface frictions. If the trend lines for these interface frictions are extended to $w/h = 16$ (the blue and green dashed lines), the line will extend down to the low peak SPL region (i.e., inside the green band), indicating non-violent failure.

This observation is possible because of the use of a prediction line (dashed line) for each interface friction which shows a consistent trend with increasing w/h ratio. The prediction lines were made as the peak SPL of coal specimens at $w/h = 12$ and 16 were mostly unavailable because the specimens did not fail after reaching 16,000 psi⁹.

It was also noticed that during the compressive loading, coal materials were intensely ejected from the specimen ribs. These ejections were recorded by the microphone as sound pressures. Figure 4.7 shows the typical sound pressure waves indicating the ejection of coal material (regions covered by the blue band) at each w/h ratio for high interface friction. It can be seen in the figure that after a certain period the compressive loading (which also can be assumed to occur after the axial stress reaches a certain level), sound pressures start to fluctuate (the areas covered by the blue band). Fluctuation is an indication of air pressure changes during the compressive loading caused by the ejection of coal material from the specimen ribs. The fluctuation continued until the specimens failed (for $w/h = 3, 4, 6,$ and 8) or decreased and stopped when the specimens did not fail ($w/h = 12$ and 16). The peak SPL from the ejections was also calculated and shown in Table 4.3. The plot of peak SPL of ejection for each specimen is shown in Figure 4.8, while the average is plotted in Figure 4.9. Three regions of the peak SPLs can also be classified as shown in each plot. For the sake of analysis, only the plot of average peak SPL (Figure 4.9) will be discussed as both plots show similar trends.

⁹ The maximum axial load applied in this research was 145,000 lbf (approximately 16,000 psi). This load limitation was made to avoid failure of sandstone platens.

Figure 4.7. Typical sound pressure waves of specimens at each w/h ratio for high interface friction (fluctuation of sound pressure waves is covered by the blue band).

Figure 4.8. The peak SPL of ejection of each specimen with three peak SPL regions (High, medium, and low peak SPL).

Figure 4.9. The average peak SPL of ejection with three peak SPL regions (High, medium, and low peak SPL).

The fluctuation of sound pressures shown in Figure 4.7 indicates that coal specimens eject coal materials after reaching a certain level of axial stress, but the violence of ejection decreases with the increase of w/h ratio and the decrease of interface friction (Figure 4.9). It can be seen in Figure 4.9 that the average peak SPL of ejection decreases from high to medium to low with the increase of

w/h ratio and the decrease of interface friction. It also can be seen in Figure 4.9 that the ejection of coal material remains violent until $w/h = 16$ for high interface friction, but starts to decrease to the non-violent region at $w/h = 8$ and even at $w/h = 4$ for medium and low interface frictions, respectively. This may indicate that in terms of the violence of coal material ejection, the influence of interface friction is more significant than w/h ratio.

The peak SPLs of coal specimens failure have been classified into three regions (high, medium, and low peak SPL) as indications of violent (high region) and non-violent failures (medium or low region). Results have shown that the violence of coal specimen failure and ejection decreases with increased w/h ratio and decreased interface friction. The influence of interface friction has also been found to be more significant at high w/h ratio than at low w/h ratio. Therefore, in terms of peak SPL as the first violent failure parameter, the hypothesis that the violence of coal specimen failure is influenced by interface friction and w/h ratio appears to receive strong support. Because of this strong correlation, it is believed that peak SPL ≥ 124 dB can satisfactorily be used for assessing the violence of coal specimen failure.

4.4 The Effect of Interface Friction and w/h Ratio on Core Zone Failure

One of the objectives of this study was to analyze the top end-surface of coal specimens after compressive loading. Figures 4.10, 4.11, and 4.12 show the typical top end-surface of coal specimens after the loading at each w/h ratio and interface friction. All the top end-surface of specimens can be seen in Appendix C.

a. $w/h = 3$ b. $w/h = 4$ c. $w/h = 6$ d. $w/h = 8$ e. $w/h = 12$ (did not fail) f. $w/h = 16$ (did not fail)

Figure 4.10. The typical top end-surfaces of coal specimens after the compressive loading at high interface friction.

a. $w/h = 3$ b. $w/h = 4$ c. $w/h = 6$ d. $w/h = 8$ e. $w/h = 12$ (did not fail) f. $w/h = 16$ (did not fail)

Figure 4.11. The typical top end-surfaces of coal specimens after the compressive loading at medium interface friction.

a. $w/h = 3$

b. $w/h = 4$

c. $w/h = 6$

d. $w/h = 8$

e. $w/h = 12$

f. $w/h = 16$ (did not fail)

Figure 4.12. The typical top end-surfaces of coal specimens after the compressive loading at low interface friction.

Four distinctive friction zones were identified based on the friction marks left after loading. The complete appearance of each zone can be seen in Figure 4.13. This figure shows the top end-surface of the specimen with $w/h = 12$ in Figure 4.11 (e). For the sake of explanation, each zone is distinguished by a white dotted line.

Figure 4.13. The four friction zones identified on the top end-surface of a coal specimen at $w/h = 12$ and at medium interface friction.

Therefore, based on the friction marks displayed on its top end-surface, a coal specimen can be divided into four friction zones that may indicate the variation of confinement within the specimen. Definition of each zone follows.

(1) Core zone

This zone occupies the center part of the specimen and does not display friction marks that indicate movement experienced on its surface during the history of loading. In addition, no cracks have initiated from or propagated toward this zone. Therefore, this zone is highly confined.

(2) Intermediate zone

This zone is located between the core zone and transition zone. It experiences slight friction as indicated by the whitish or sometimes light dark scratches on its surface. Since movement is already shown in this zone, the confinement in this zone is less than that in the core zone, but

greater than that in the transition zone. Cracks may or may not have initiated from or propagated toward this zone.

(3) Transition zone

This zone is located between the transition zone and rib zone. It experiences intense friction as indicated by the reddish scratches on its surface. The confinement in this zone is much less than that in the intermediate zone, but greater than that in the rib zone, hence the name “transition zone”. Cracks may have initiated from or propagated toward this zone.

(4) Rib zone

This zone is located at the outermost part of the specimen, outside the transition zone. It has no or very little confinement as it is exposed directly to free space. This zone may fail shortly after the compressive load is applied. Cracks progressively propagate from this zone toward the transition zone, exposing the transition zone to new free space.

The discovery of these four zones may extend the previous findings of Holland and Thomas (1954) about probable stress distribution in a pillar, the three zones of confinement in a yield pillar proposed by Morsy (2003), and elastic core observed by Lu et al. (2008) in FLAC^{3D} modeling.

In addition, these four zones always appear in an orderly manner with the slightly or less confined section being at the outermost and the highly confined being at the innermost (center) portions of the specimen. These four zones may not be seen clearly on the top end-surface of each specimen, particularly at low w/h ratio or at medium and low interface frictions. In these conditions, the intermediate and transition zones are barely seen as they may join together. This is probably because the confinement for each zone has not been fully developed, making the friction marks barely distinguishable. Table 4.4 summarizes percent area and average percent area of the four zones that have been defined previously. Violent and non-violent failure as indicated in Table 4.4 is based on specimens' peak SPL as shown in Table 4.3 (violent if its peak SPL ≥ 124 dB and non-violent if its peak SPL < 124 dB).

Table 4.4 Summary of Area, Percent Area, and Average Percent Area of Friction Zones at Each Interface Friction and w/h Ratio

Interface friction	Specimen code	w/h	Core zone profile	Area, in ²					Percent area (%)				Average percent area (%)			
				Total	Core	Intermediate	Transition	Rib	Core	Intermediate	Transition	Rib	Core	Intermediate	Transition	Rib
High (0.4)	3c-ucs 3	3	No core	14.7	0.0	0.0	6.6	8.1	0.0	0.0	45.1	54.9	0.0	0.0	45.8	54.2
	3c-ucs 8	3		25.9	0.0	0.0	11.6	14.3	0.0	0.0	44.8	55.2				
	3c-ucs 9	3		18.4	0.0	0.0	6.9	11.5	0.0	0.0	37.4	62.6				
	3c-ucs 12	3		24.8	0.0	0.0	13.9	10.9	0.0	0.0	55.9	44.1				
	3c-ucs 16	3		13.3	0.0	0.0	3.4	9.9	0.0	0.0	25.4	74.6				
	4c-ucs 2	4	No core	9.2	0.0	0.6	2.0	6.6	0.0	6.6	21.3	72.2	0.8	17.4	36.7	45.9
	4c-ucs 8	4		21.6	0.0	2.8	3.0	3.5	0.0	30.2	32.2	37.6				
	4c-ucs 20	4		9.2	0.0	1.4	5.2	2.6	0.0	15.5	56.6	27.9				
	4c-ucs 4	4	Failed	9.2	0.7	4.4	7.1	7.3	4.6	22.4	36.0	36.9	4.1	32.6	28.8	34.6
	6c-ucs 1	6	Failed	21.0	0.7	6.3	5.8	8.1	3.6	30.2	27.7	38.6				
	6c-ucs 4	6		21.3	1.1	7.5	5.8	6.9	5.3	35.1	27.4	32.2				
	6c-ucs 5	6	Failed	20.9	0.7	6.8	6.6	6.9	3.3	32.4	31.4	32.9	23.2	30.2	22.0	24.5
	8c-ucs 14	8		19.7	0.9	4.4	7.1	7.3	4.6	22.4	36.0	36.9				
	8c-ucs 3	8	Failed	16.0	0.9	4.1	5.8	5.2	5.9	25.8	35.9	32.4				
	8c-ucs 10	8		13.8	5.5	4.3	0.0	4.1	39.7	30.8	0.0	29.4				
	8c-ucs 9	8	Intact	12.8	6.0	4.7	0.0	2.2	46.6	36.4	0.0	17.0	33.8	24.3	26.0	15.9
	8c-ucs 13-1	8		9.2	1.8	3.3	3.5	0.6	19.3	35.8	38.1	6.9				
	12c-ucs 11	12	**	11.9	3.1	2.4	4.5	1.8	26.4	20.3	37.8	15.5				
	12c-ucs 16	12		12.0	2.9	4.2	2.4	2.5	23.9	35.2	20.3	20.6				
	12c-ucs 17	12		11.3	4.2	1.9	3.3	1.9	37.4	16.8	29.2	16.5				
	12cucs 5	12	**	12.6	5.9	3.1	2.1	1.4	47.3	24.9	16.7	11.0	71.1	14.3	11.4	3.2
	16c-ucs 7	16		9.2	4.4	1.4	2.7	0.7	47.9	15.4	28.9	7.9				
	16c-ucs 6	16		9.9	8.1	1.1	0.5	0.2	82.1	11.0	5.2	1.7				
	16c-ucs 4	16		9.9	8.3	1.6	0.0	0.0	83.4	16.6	0.0	0.0				
Medium (0.22)	3c-ucs 14	3	No core	10.4	0.0	0.0	1.2	9.2	0.0	0.0	11.7	88.3	0.0	11.7	13.1	75.2
	3c-ucs 2	3		12.0	0.0	0.0	0.9	11.1	0.0	0.0	7.9	92.1				
	3c-ucs 4	3		12.8	0.0	2.5	1.7	8.6	0.0	19.5	13.5	67.1				
	3c-ucs 15	3		16.2	0.0	4.4	3.2	8.6	0.0	27.3	19.5	53.2				
	4c-ucs 23	4	No core	13.1	0.0	0.9	3.8	8.4	0.0	7.2	29.1	63.7	0.0	13.4	33.0	53.7
	4c-ucs 15	4	*	22.6	0.0	2.3	5.5	10.8	0.0	12.6	29.5	57.9				
	4c-ucs 14	4		18.2	0.0	3.1	6.2	6.1	0.0	20.3	40.4	39.4				
	6c-ucs 2	6	*	16.1	1.0	5.5	3.1	4.5	6.7	36.3	27.1	29.8	6.0	36.8	22.7	33.5
	6c-ucs 8	6	No core	18.0	0.9	6.0	3.0	6.0	5.4	37.3	18.4	37.2				
	8c-ucs 4	8	*	13.9	2.1	6.4	1.4	2.7	16.9	50.9	11.1	21.2	11.9	42.1	20.9	25.1
	8c-ucs 13	8		15.2	1.0	4.7	3.3	3.1	6.9	33.3	30.7	29.1				
	12c-ucs 11-1	12	**	13.8	1.9	5.4	2.9	2.4	15.3	42.8	23.1	18.8	24.7	39.6	21.4	13.2
	12c-ucs 13	12		13.8	1.1	6.6	3.8	2.3	8.3	47.9	27.2	16.6				
	12c-ucs 12	12		9.4	4.7	2.6	1.3	0.7	50.5	28.2	14.0	7.3				
	16c-ucs 2	16	**	11.8	5.4	3.0	2.2	1.0	46.5	25.8	18.7	9.1	57.6	23.3	12.1	6.9
	16c-ucs 1	16		10.9	6.8	2.1	0.6	0.5	68.8	20.8	5.6	4.8				

Interface friction	Specimen code	w/h	Core zone profile	Area, in ²					Percent area (%)				Average percent area (%)			
				Total	Core	Intermediate	Transition	Rib	Core	Intermediate	Transition	Rib	Core	Intermediate	Transition	Rib
Low (0.13)	3c-ucs 6	3	No core	15.4	0.0	0.0	3.1	12.3	0.0	0.0	20.0	80.0	0.0	0.0	19.7	80.3
	3c-ucs 5	3		10.3	0.0	0.0	3.4	6.9	0.0	0.0	32.7	67.3				
	3c-ucs 18	3		13.2	0.0	0.0	0.9	13.3	0.0	0.0	6.4	93.6				
	4c-ucs 18	4	No core	13.1	0.0	0.0	3.2	7.4	0.0	0.0	36.2	63.8	0.0	0.0	29.7	70.3
	4c-ucs 5	4		16.9	0.0	0.0	3.7	11.0	0.0	0.0	25.0	75.0				
	4c-ucs 17	4		15.4	0.0	0.0	2.5	8.7	0.0	0.0	22.6	77.4				
	4c-ucs 22	4	*	17.5	0.0	0.0	4.8	7.7	0.0	0.0	38.2	61.8	0.0	0.0	47.4	52.6
	4c-ucs 1	4		17.0	0.0	0.0	3.8	10.5	0.0	0.0	26.3	73.7				
	6c-ucs 6	6	No core	21.0	0.0	0.0	9.7	11.3	0.0	0.0	46.4	53.6	0.0	0.0	47.4	52.6
	6c-ucs 7	6		22.2	0.0	0.0	10.8	11.4	0.0	0.0	48.5	51.5				
	8c-ucs 21	8	*	19.5	0.0	3.2	5.2	10.2	0.0	21.3	26.7	52.0	0.0	36.6	19.5	43.9
	8c-ucs 5	8		15.3	0.0	5.6	3.2	6.4	0.0	36.8	21.1	42.1				
	8c-ucs 19	8		15.6	0.0	5.4	4.0	6.2	0.0	34.8	25.4	39.8				
	8c-ucs 16	8		16.2	0.0	6.7	2.2	7.3	0.0	41.5	13.3	45.1				
	8c-ucs 17	8		16.2	0.0	7.9	1.8	6.6	0.0	48.7	10.9	40.4				
	12c-ucs 7	12	*	12.7	0.0	9.6	1.6	1.5	0.0	75.5	12.8	11.8	0.0	72.0	12.0	16.0
	12c-ucs 9	12		15.8	0.0	8.5	2.7	4.6	0.0	53.4	17.4	29.2				
	12c-ucs 10	12		12.7	0.0	9.6	1.1	1.9	0.0	76.1	8.5	15.4				
	12c-ucs 8	12		12.6	0.0	10.5	1.2	1.0	0.0	83.0	9.2	7.8				
	16c-ucs 3	16	**	11.1	0.9	10.0	0.9	0.1	8.6	90.8	7.9	1.3	9.3	80.2	9.9	4.9
	16c-ucs 15	16		10.7	1.1	7.4	1.3	0.9	10.1	69.7	11.8	8.5				

* Specimens failed non-violently as its peak SPL < 124 dB.

** Specimens did not fail within the axial stress of 16,000 psi.

The average percent area of each friction zone at each w/h ratio is plotted for different interface frictions in Figure 4.14, and the plot of friction zones from each specimen can be seen in Appendix D. One important point which emerges from Figure 4.14 is that, regardless of interface friction, there are opposite trends between core and rib zones with increasing w/h ratios. At any interface friction, average percent area of core zones shows an increasing trend with increasing w/h ratios, while the opposite is observed for rib zones. The trend becomes more obvious when the average ratio of core to rib zone is plotted as in Figure 4.15. Average ratio of core to rib zone shows an increasing trend with increasing w/h ratio, but the ratio decreases with decreasing interface friction.

Since core zone is a highly confined zone, the trends observed from Figure 4.14 and 4.15 indicate that confinement developed within a coal specimen increases with increasing w/h ratio but decreases with decreasing interface friction. This may explain why the strength of coal specimens is higher at high w/h ratio and interface friction than at low w/h ratio and interface friction (section 4.5). Even though confinement has been subject of many investigations on the strength of coal specimens, the findings of this study offer true physical proof. In fact, in this research, the average percent area of confinement was measured as the core zone.

It has been explained in section 4.3 that the violence of coal specimen failure decreases with the increase of w/h ratio and the decrease of interface friction. On the other hand, it has been clearly explained that confinement increases with the increase of w/h ratio and decreases with the decrease of interface friction. This may indicate that, at the same interface friction, the increase in confinement due to the increase in w/h ratio may reduce the violence of specimen failure. It is also noticed that by the increase of confinement, the decrease of rib zone is expected as well as the decrease of violence of failure. Hence, it may also be necessary to consider that violent failure of a coal specimen may actually be a result of rib zone failure.

The intermediate and transition zones show a decreasing trend starting from $w/h = 6$ at high and medium interface frictions, but both zones show an opposite trend at low interface friction. At $w/h = 3$ and 4, the initial trends of these two zones vary among interface frictions. Because of this inconsistency, the effect of these zones on coal specimen failure is not fully understood.

a. High interface friction

b. Medium interface friction

c. Low interface friction

Figure 4.14. The average percent area of each friction zone at each w/h ratio and interface friction.

Figure 4.15. The average ratio of core to rib zone at each w/h ratio and interface friction.

It has been found that several coal specimens at high interface friction failed violently when the core zones failed (Table 4.4). However, this was not true for the violent failures at other w/h ratios and at medium and low interface frictions.

As stated in section 4.3.1, according to its peak SPL and regardless of interface friction, violent failures of coal specimens mostly occur at $w/h = 3, 4$, and 6 . As shown in Figure 4.14, at $w/h = 3$ and 4 and regardless of interface frictions, violent failures occurred without the existence of a core zone. This is shown by the fact that the average percent area of core zone at these w/h ratios was almost zero. This is also true for $w/h = 6$ at low interface friction. Therefore, at low w/h ratio, no correlation can be established regarding the relationship between core zone failure and the violence of coal specimen failures. Figure 4.16a shows a typical top end-surface of specimen that failed violently without the existence of a core zone, while Figure 4.16b shows the top end-surface of specimen that failed violently and also had a failure of the core zone.

The essential of core zone failure to exhibit violent failure still remains uncertain for specimens at high w/h ratio due to the limitation of axial loads applied (up to 145,000 lbf). Most of the specimens at $w/h \geq 12$ did not fail within that applied load. In some cases, violent failures

occurred even when the core zones did not fail. The core zones remained intact within the specimen and only materials from the rib zones were ejected. This may be a typical violent failure of the rib zone (Figure 4.16c).

Figure 4.16. Typical core zone profiles of specimens that failed violently at high interface friction.

Thus, as the second violent failure parameter in this research, core zone failure was found not to be a necessary condition for violent failure of coal specimen at low w/h ratios, but its applicability to high w/h ratios remains unknown. According to Morsy's (2003) hypothesis that core zone failure will cause pillar bump, the results in this research suggest that this depends on w/h ratio. Therefore, the correlation between core zone failure and violent failure of coal specimen appears to deserve more investigation, particularly for specimens at high w/h ratios.

4.5 The Effect of Interface Friction and w/h Ratio on Ultimate Stress

Table 4.5 summarizes the mode of failure of each specimen and its ultimate stress at failure (σ_u) at each w/h ratio and interface friction. Violent or non-violent failure was determined based on peak SPL as presented in Table 4.3; that is, failure was considered violent if its peak SPL ≥ 124 dB and non-violent if its peak SPL < 124 dB.

Variations of specimens' post failure behavior and ultimate stress with w/h ratio and interface friction are shown in Figure 4.17 and 4.18, respectively. In general, with the increase of w/h ratio, specimens' post-failure behaviors changed from complete failure, to failure and strength regaining, to strain hardening, to highly elastic (did not fail). This indicates an increasing trend in specimen strength with the increase of w/h ratio, which is also shown by the increase in ultimate stress in Figure 4.18. Conversely, with the decrease of interface friction, the ultimate stress of specimens at failure shows a decreasing trend. This decrease in strength is also shown in Figure 4.17 by the fact that there is an increasing amount of axial strain experienced by coal specimens with the decrease of interface friction. Therefore, the strength of coal specimens increases with increasing w/h ratio and decreases with decreasing interface friction.

This is not a surprising finding because the influence of w/h ratio and interface friction on compressive strength of coal specimens has been observed by many investigators (Babcock, 1985; Daniels & Moore, 1907; Griffith & Conner, 1912; Khair, 1968; Meikle & Holland, 1965; Pariseau et al., 1977). The data shown in Figures 4.17 and 4.18 confirm previous findings.

Table 4.5 Summary of Mode of Failure and Ultimate Stress of Specimens at Each w/h Ratio and Interface Friction

High interface friction					Medium interface friction					Low interface friction				
Specimen code	w/h	Mode of failure	σ_u (psi)	Average σ_u (psi)	Specimen code	w/h	Mode of failure	σ_u (psi)	Average σ_u (psi)	Specimen code	w/h	Mode of failure	σ_u (psi)	Average σ_u (psi)
3c-ucs 3	3	Violently	3,746	4,512	3c-ucs 14	3	violently	3,517	3,619	3c-ucs 5	3	violently	3,385	3,392
3c-ucs 8	3		3c-ucs 2		3	3,575		3c-ucs 6		3	3,480			
3c-ucs 9	3		3c-ucs 4		3	3,685		3c-ucs 18		3	3,312			
3c-ucs 12	3		3c-ucs 15		3	3,701		4c-ucs 22		4	4,207			
3c-ucs 16	3		4,699		4c-ucs 23	4	violently	4,324	4,212	4c-ucs 1	4	Non- violently	4,130	4,139
4c-ucs 2	4	Violently	5,323	5,068	4c-ucs 15	4		4,255		4c-ucs 18	4	violently	4,143	
4c-ucs 4	4		5,000		4c-ucs 14	4		4,056		4c-ucs 5	4		4,144	
4c-ucs 8	4		4,951		6c-ucs 8	6	violently	6,848	4c-ucs 17	4	4,039			
4c-ucs 20	4		5,000		6c-ucs 2	6	non-violently	6,561	6c-ucs 6	6	5,467	5,261		
6c-ucs 4	6	Violently	7,605	7,374	8c-ucs 4	8	Non-violently*	12,540	12,388	6c-ucs 7	6		5,054	
6c-ucs 1	6		7,613		8c-ucs 13	8		12,235		8c-ucs 21	8	7,063	7,984	
6c-ucs 5	6		6,903		12c-ucs 11-1	12	Did not fail	-	-	8c-ucs 5	8	8,082		
8c-ucs 14	8	Violently*	14,624	14,657	12c-ucs 13	12		-	-	8c-ucs 19	8	10,631		
8c-ucs 3	8		14,318		12c-ucs 12	12		-	-	8c-ucs 16	8	7,065		
8c-ucs 10	8		14,601		16c-ucs 2	16	Did not fail	-	-	8c-ucs 17	8	7,077		
8c-ucs 9	8		14,316		16c-ucs 1	16		-	-	12c-ucs 7	12	15,202	15,083	
8c-ucs 13-1	8		15,424							12c-ucs 9	12	15,079		
12c-ucs 11	12	Did not fail	-	-						12c-ucs 10	12	14,126		
12c-ucs 16	12		-	-						12c-ucs 8	12	15,924		
12c-ucs 17	12		-	-						16c-ucs 3	16	-	-	
12cucs 5	12		-	-						16c-ucs 15	16	-	-	
16c-ucs 7	16	Did not fail	-	-										
16c-ucs 6	16		-	-										
16c-ucs 4	16		-	-										

* Exhibited strain hardening behavior before the failure.

a. High interface friction

b. Medium interface friction

c. Low interface friction

Figure 4.17. The typical stress-strain curves of coal specimens at each w/h ratio and interface friction.

Figure 4.18. The ultimate stress of specimens at failure.

The ultimate stresses of coal specimens that failed non-violently (from Table 4.5) are shown with black symbols in Figure 4.19. It is clear that an ultimate stress as high as 15,000 psi ($w/h = 8$) or as low as 3,000 psi ($w/h = 3$) is able to cause a coal specimen to fail in a violent fashion. Specifically, regardless of interface frictions, a relatively low stress has been found to be sufficient to fail coal specimens violently at low w/h ratios ($w/h = 3, 4$, and 6). Conversely, even relatively high stress could not fail the specimen violently at $w/h \geq 8$ when the interface friction was either medium or low (as shown by the black symbols); non-violent failures occurred at $w/h = 12$ and at low interface friction even though the stress was as high as 15,200 psi.

Figure 4.19. The ultimate stress of coal specimens that failed violently and non-violently

In summary, these results clearly show that the violence of coal specimen failure does not correspond to high stress alone. In fact, the violence of failure greatly depends on w/h ratio and interface friction. Furthermore, interface friction has a more significant influence in reducing the violence of failure at high w/h ratio than it does at low w/h ratio.

This result narrows the findings from Babcock and Bickel (1984) that stress and constraint are necessary conditions for coal burst. The results of this research show that stress is needed to fail the specimen, but it is the interface friction that greatly influences the violence of the failure; the influence is more significant at high w/h ratio than at low w/h ratio. Therefore, as the third violent failure parameter in this research, high ultimate stress cannot be used to assess the violence of coal specimen failure.

4.6 Contribution of This Research to Coal Mine Bumps

Several inferences can be drawn from this research that may be useful in gaining a better understanding of the phenomenon of coal mine bump.

The results of this research have shown that peak SPL is reliable for use in assessing the violence of coal specimen failure. Thus, it may be reasonable to consider the likelihood of coal pillars to produce bumps by predicting the likelihood of coal specimens to fail violently at high peak SPL (≥ 124 dB). Coal pillars may also produce small bumps during loading such as bouncing of coal material from the pillar ribs. The bouncing may also be violent depending on w/h ratio and interface friction. Therefore, the bouncing of coal material may be useful as an early indication of imminent pillar bump. Continuing to put more load on these pillars may lead to bumps.

Rib failure may also contribute to the violence, particularly at high w/h ratio. This type of failure may not result in the failure of the whole pillar, but it may throw coal material from pillar ribs in a violent fashion.

High stress may not be a necessary condition to produce bumps. The general belief that a great overburden depth or strong immediate roof and floor creates a high stress condition in the pillar as a necessary condition for bumps needs to be reconsidered. Stress alone may contribute to the failure of the pillar, but it may be the friction between the pillar and the immediate roof and floor that determines the degree of the violence. Coal pillars at low w/h ratios may also be more prone to bump than pillars at high w/h ratio as the confinement developed within a stressed pillar at high w/h ratio may reduce the violence of pillar failure.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The methods used in this research were intended to reveal the influence of interface friction and w/h ratio on the violence of coal specimen failure. Three violent failure parameters (peak SPL, core zone failure, and ultimate stress) were adopted to assess the violence of coal specimen failure. Peak SPL was the base parameter for assessing violence. The violence of coal specimen failure was investigated at three different interface frictions (high: $\mu = 0.40$, medium: $\mu = 0.22$, and low: $\mu = 0.13$) and six w/h ratios (w/h = 3, 4, 6, 8, 12, and 16). The following conclusions can be drawn from this study:

The violence of coal specimen failure was found to decrease with increasing w/h ratio and decreasing interface friction. In terms of peak SPL and ultimate stress, the influence of interface friction in reducing violence of failure was more significant for coal specimens at high w/h ratios than at low w/h ratios; regardless of interface friction, coal specimens were more prone to fail violently at low w/h ratios.

The high peak SPL region ≥ 124 dB was shown to be the most reliable parameter for assessing the violence of coal specimen failure. Thus, it may be useful to predict the proneness of coal pillars to produce bumps from the likelihood of a coal specimen to fail with peak SPL within this region. Bouncing of coal material from pillar ribs may be also useful as an early indication of future pillar bumps. Putting more loads on the pillar may lead to bumps.

The application of core zone failure to produce violent failure depends on w/h ratio. It was found that core zone failure was not a necessary condition to cause the coal specimens to fail in a violent

fashion, particularly at low w/h ratios. More investigation is needed to show consistency in producing the violent failure at high w/h ratios.

The violence of coal specimen failure was found to be independent of high ultimate stress. Stress alone is needed to cause the failure of the specimen, but it is the interface friction that greatly influences the degree of the violence. The general belief about geological conditions creating a high stress condition in pillars as a necessary condition for coal bumps deserves to be reconsidered. The stress may only contribute to pillar failure, while the friction between the pillars and the immediate roof and floor may determine the violence of the failure.

There are four friction zones on the top end-surface of a coal specimen that may indicate the variation of confinement within the specimen. In order from the highest confinement (innermost) to the weakest (outermost), these zones are: core zone, intermediate zone, transition zone, and rib zone.

The zone of confinement has been found to increase with increase in w/h ratio. Moreover, at the same interface friction, the increase of the confinement may also reduce the violence of failure.

5.2 Recommendations

There is much room for further advancement of this study. Some potential future improvements are presented below.

The number of coal specimens at each w/h ratio needs to be increased. Future studies also need to be carried out for higher coefficients of friction (μ) in order to reflect real friction conditions between coal pillar and immediate roof and floor.

Stronger loading platens than sandstone are recommended for use in order to increase the applied axial load. This is very much necessary in order to obtain more comprehensive violent failure parameters for specimens at high w/h ratios, especially w/h ratio ≥ 12 .

Greater digitization will help the ImageJ software to recognize the different colors among the friction zones. This is necessary to reduce the possibility of error due to the subjectivity of the researchers when manually determining the boundary of each zone in Adobe Photoshop Element 4.0 as was done in this study.

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Appendix A: Stress-strain curve (High interface friction)

Stress-strain curve (Medium interface friction)

Stress-strain curve (Low interface friction)

Appendix B: Sound Pressures Wave (High interface friction)

Medium interface friction

Low interface friction

Appendix C: Top End-Surface of Coal Specimens after the Compressive Loading

High interface friction

Medium interface friction

Low interface friction

Appendix D: Percent Area of Friction zones of Each Specimen

a. High interface friction

b. Medium interface friction

c. Low interface friction

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