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# Brittle-ductile transition in coal pillar failures

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# BRITTLE-DUCTILE TRANSITION IN COAL PILLAR FAILURES

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*ABSTRACT:* Factor of Safety (FoS) is the most widely used empirical criterion in coal pillar design. The increased vertical stresses associated with deep mining are resulting in pillar sizes much larger than those used in the development of the empirical strength formula. It is not uncommon to see pillars with over 50 m solid widths based on the established design criteria, which reduces overall reserve recovery and development productivity. Previous research revealed that pillars will transform from brittle to ductile failure with strain-hardening behaviour when their w/h ratio exceeds a certain critical value. However, the actual failure mechanics of pillars with different w/h ratios have largely been understudied. This paper discusses whether a coal pillar with a critical w/h ratio and reduced FoS can achieve functionality to allow more flexibility in pillar design for mine layout optimization. Using the more advanced laboratory testing and monitoring equipment that is now available, the failure mechanics of coal samples with different dimensions are investigated through uniaxial compression tests. The w/h value at which in situ pillar behaviour would be expected to transform from brittle to ductile is then considered and discussed further, including the research program that would enable the findings to be safely applied in deep underground mines.

## INTRODUCTION

Coal pillars are the coal columns left in place to support the overlying strata through their bearing or yielding capacity. The two primary types of coal pillars in longwall mining are: (i) chain pillars for maintaining the serviceability of gateroads during longwall extraction, and (ii) mains heading pillars for providing long-term serviceability of mains headings (Hill, 2005). Chain pillars are required to perform their role until the last of the adjacent longwall panels have passed by, whereas mains pillars are expected to remain stable for the life of the mine and beyond. Besides, pillar dimensions are the constraint to determining the amount of required roadway development. The Factor of Safety (FoS) criterion is the most widely employed methodology to ensure the long-term stability of coal pillars. It requires that the FoS, i.e. the ratio of pillar strength to the assumed stress, should be no less than a designed FoS that it is considered will ensure that the pillars have the available resisting capacity to support the overlying strata (Frith and Reed, 2018). In Australia, the UNSW empirical pillar design formula - founded on extensive databases of mining practices - is widely adopted (Galvin, 2006, Vardar *et al.*, 2019):

$$\sigma_{ps} = 8.6\, w^{0.51}/h^{0.84} \tag{1}$$

where $\sigma_{ps}$ is the pillar strength; and $w$ and $h$ are the pillar width and height, respectively. For a pillar system with mining depth $H$ and roadway width $W$, based on the tributary area theory (TAT), the applied stress on a coal pillar with be:

$$\sigma = \gamma H \frac{w + W}{w} \tag{2}$$

where $\gamma$ is the average bulk density of rock strata.

As shown in Equations 1 and 2, pillar dimensions are the key design factors for both pillar strength estimation and induced stress in a pillar. To ensure the stability of coal pillars subject to gravitational stress applied by the overlying strata, the pillar size needs to be large enough to meet the adequate FoS by reducing the stress and increasing the strength of the designed pillars. However, the current pillar design methodology often suggests very large pillars for the deep geo-stress environment since only size and shape factors are considered for the strength of coal pillars (Ünlü, 2001). For instance, according to the UNSW formulation, the pillar widths for a typical roadway system will increase from 21 m for 300 m to 43 m for 500 m mining depth as shown in **Figure 1**. Therefore, it is not uncommon to

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see pillars with over 50 m solid widths in current mining layouts, which reduces overall reserve recovery and development productivity.

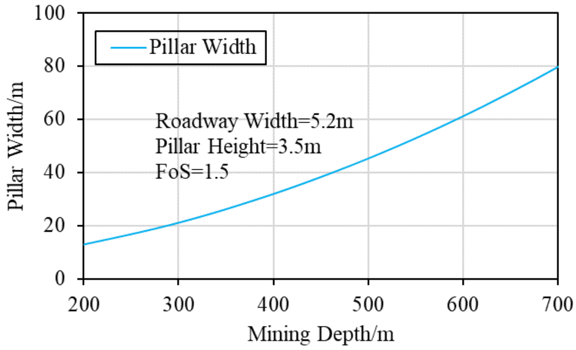



**Figure 1: Pillar width increases with mining depth for roadways with 5.2m width and 1.5 FoS**

In a highly regarded work by Das - using laboratory tests of Indian coal samples with a wide range of w/h ratio from 0.5 to 13.5 - it was found that coal post-failure strength is positively related to the w/h ratio (**Figure 2**) (Das, 1986). Further research has extended these results and it is evident that the cores of coal pillars remain almost intact with ductile behaviour when the w/h ratios are greater than ~4 (Reed *et al.*, 2017, Frith and Reed, 2018, Kim and Larson, 2021). Besides, the failure violence of pillars on the rib is independent of the strength but relevant to the w/h ratio and roof/floor conditions (Prassetyo et al., 2011). Apart from the size and pillar shape, however, ultimate failure strength in coal (and rock-like materials) is also a function of 2D or 3D nature of the applied loads, fracture propagation through rock bridges or pre-existing defects, and ductile to brittle stress limits (Serati et al., 2014, Serati et al., 2020, Zhu et al., 2022). Nevertheless, the one aspect of coal pillar failures that is yet largely understudied is the actual failure mechanics of pillars with different w/h ratios. It is necessary to look beyond the strength concept to be able to obtain further assurance of stability and failure behaviour based on the pillar w/h ratio. In order to comprehend the failure mechanism of pillars with different w/h ratios and therefore to seek a solution for the oversized pillars in deep mining, the strength and failure characteristics of coal samples with different dimensions are investigated in this study under uniaxial stress states. The w/h value at which *in situ* pillar behaviour would be expected to transform from brittle to ductile is then explored and discussed further, including the research program that would enable the findings to be safely applied in deep underground mines.

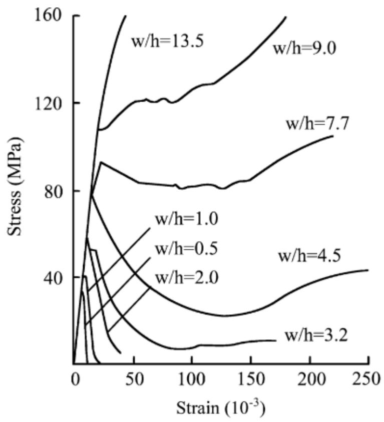



**Figure 2: The typical stress-strain behaviour of coal for varying w/h ratios (Das, 1986)**

## EXPERIMENTAL

Coal blocks from a local coal mine in Queensland were processed into square coal samples with 70 mm in width and different heights through the cutting and grinding process by the equipment shown in **Figure 3**. The samples were ground flat to 0.1 mm across the face as checked by Rock Surface Flatness Verification Apparatus. All samples were stored in an oven at 105°C until the loss of coal mass between successive drying periods was less than 0.1% of the initial mass to eliminate the moisture effects caused by the wet cutting and grinding process. The average moisture content of the coal samples calculated based on the mass losses is 5.03%.

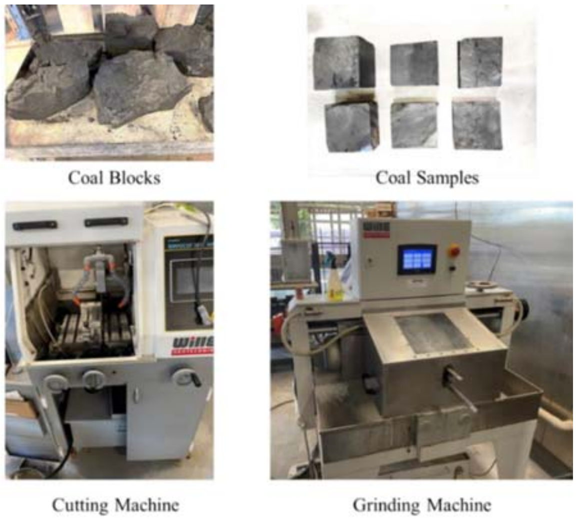



**Figure 3: Coal samples prepared via cutting and grinding**

The tests were performed using an Instron 250 kN Compression Testing Machine at a controlled displacement rate of 0.1 mm/min. Samples were placed at the centre of a spherical seat to ensure that the load was averagely applied to the samples. The acquired stress-strain curves for coal samples are plotted in **Figure 4**. The loading process of sample 70-16-1 was beyond the capacity (250 kN) of the testing machine. The pre- and post-failure curves of all the other samples were determined. With the increase of the w/h ratio from 1 to 2.26, the strength of coal samples has obviously increased. The strength increases for samples with a w/h ratio from 2.26 to 4.38 is not obvious. Besides, coal samples tend to have ductile behaviour for the post-failure process with the increase of w/h ratio as suggested by stress-strain curves. The major failure of coal samples with the same w/h ratio is at the same strain level. However, different from previous research, the elasticity of samples has shown a negative correlation to the w/h ratio, which means the samples will have more plastic pre-failure behaviour with the increase of the w/h ratio. A summary of the mechanical parameters of coal samples is listed in **Table 1**.

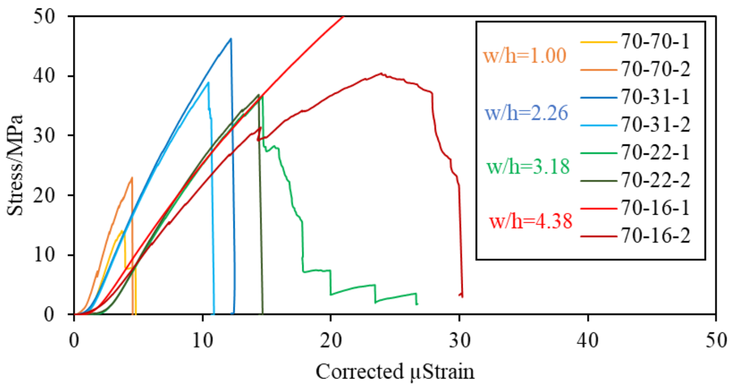


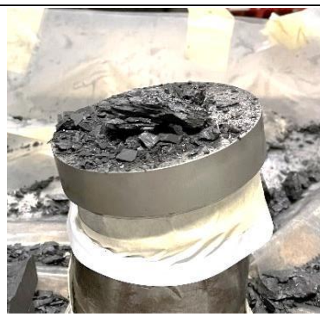
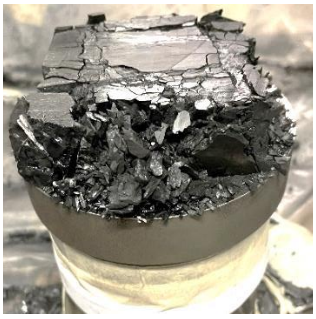
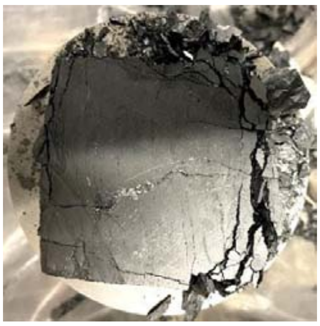

**Figure 4: Stress-strain curves of coal samples with different w/h ratios**

**Table 1: Summary of the mechanical parameters of coal samples with different w/h ratios**

| Sample | Failure Force [kN] | Failure Displacement [mm] | Failure Mode | Elastic Modulus [GPa] |
|---|---|---|---|---|
| 70-70-1 | 69.07 | 1.73 | Bursting | 6.63 |
| 70-70-2 | 112.74 | 1.90 | Axial Splitting with Bursting | 6.64 |
| 70-31-1 | 226.89 | 1.81 | Multiple Fracturing | 4.53 |
| 70-31-2 | 190.91 | 1.66 | Multiple Fracturing with Bursting | 4.36 |
| 70-22-1 | 179.41 | 1.69 | Axial Splitting | 3.12 |
| 70-22-2 | 180.84 | 1.65 | Severe Axial Splitting | 3.23 |
| 70-16-1 | N/A | N/A | N/A | 2.82 |
| 70-16-2 | 198.46 | 1.93 | Fracturing | 2.05 |

A more obvious brittle-ductile transmission of coal samples can be observed from the failure process. **Table 2** summarizes the failure behaviour and post-failure conditions of coal samples with different w/h ratios. The coal samples had a violent, brittle failure with coal ejections when the w/h ratio is 1. The failure was gentler at the w/h ratio of 2.26. For coal samples with a w/h ratio of 3.18, the failure behaviours of coal samples changed from violent ejections to pressure bumps without large-scale coal particle ejections. As the w/h ratio increased to 4.38, the edges of coal samples were pulverized under the uniaxial compression load with a very gentle failure process. Besides, the cores of the samples were still intact. Considering the samples have been dried in an oven with significantly low humidity, the samples had more brittle failure than would be expected in their natural state. The long-term residual strength and strain hardening effect were not observed for samples with w/h ratios above 4. But the failure process was changed from brittle to ductile failure with lower sound and gentler ejection.

**Table 2: Summary of failure characteristics of coal samples with different w/h ratios**

| Sample Dimension | w/h Ratio | Failure Behaviour | Post-failure Pictures |
|---|---|---|---|
| w=70 mm<br>h=70 mm | 1.00 | Violent failure with coal bursts and loud sound. |   |
| w=70 mm<br>h=31 mm | 2.26 | Several moderate failures and coal bursts. |   |
| w=70 mm<br>h=22 mm | 3.18 | Several small-scale coal particle ejections, Pressure bumps at residual stage. |   |
| w=70 mm<br>h=16 mm | 4.38 | Very small-scale coal particle ejections from the edge with lower sound. The final failure is associated with pressure bump. |   |

## DISCUSSIONS

### Bearing Capacity

It has been suggested by previous research that the bearing capacity of coal will increase with w/h ratios (Sharipov and Adoko, 2021). However, based on limited test results in this study, the strength has no obvious change for samples with 2.26 and 3.18 w/h ratios. The inhomogeneous properties and natural weaknesses could be a reason causing the randomness of the test results. But the coal pillar strength will also not have a significant increase due to the discontinues within coal masses (Medhurst and Brown, 1998, Poulsen and Adhikary, 2013). **Figure 5** is a numerical simulation of a 3 m height coal pillar with w/h ratios from 0.5 to 10 based on highwall mining cases in South Africa. The strength formulas and numerical simulations generally describe a regressive strength increase with increasing width-to-height ratio (Vardar et al., 2019, Mo *et al*., 2018, Gao et al., 2014, Mathey and Van der Merwe, 2016). The post-failure modulus of coal pillars was non-linearly dependent on the w/h ratio, which indicated a potential strain hardening effect once the w/h ratio is larger than 3 (Jaiswal and Shrivastva, 2009). There is a potential critical w/h ratio for coal pillars to reach their maximum benefits from the bearing capacity perspective.

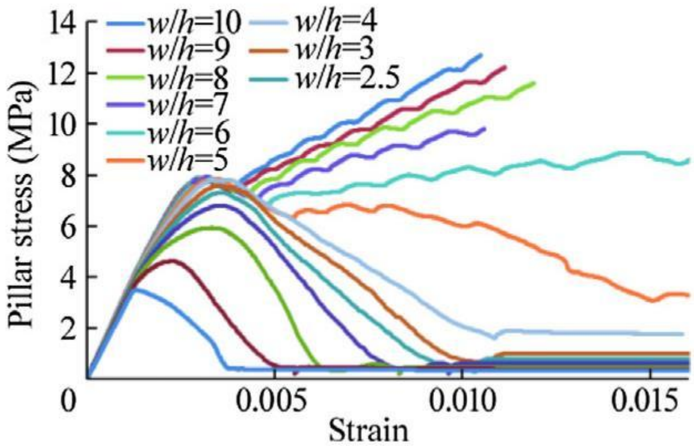



**Figure 5: Numerical results of coal pillar model with w/h ratios from 0.5 to 10 (Mo et al., 2018)**

### Pillar Burst

The remaining coal pillars can have severe bursts associated with coal block ejections in high projectile velocity under the effects of supercritical stresses. The pillars with a significant strain softening characteristic, which typically have a low to relatively low w/h ratio, is at the greatest bursts risk (Gale, 2018). Those strain-softening pillars will have a sharp stress decrease and violent failure after peak strength as illustrated by **Figure 6**. The pillars with a w/h ratio of less than 1.5 have been associated with bursts collapse (Seedsman, 2022).

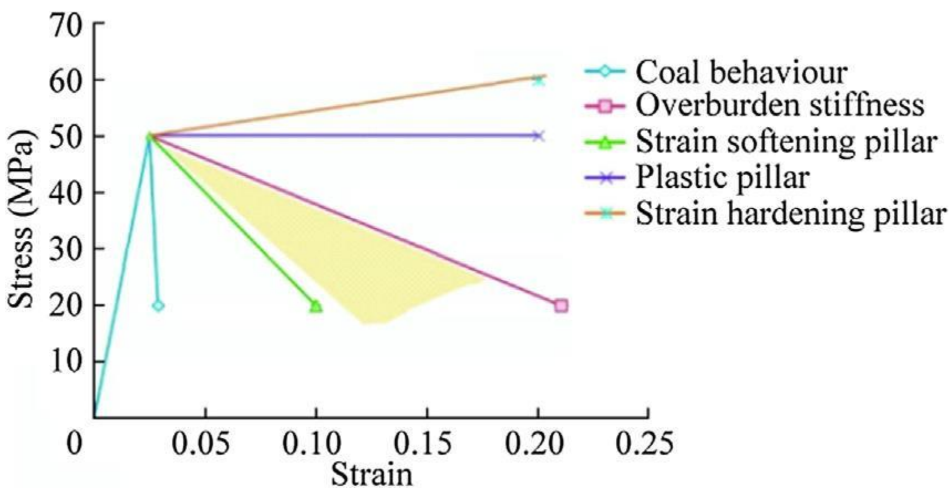



**Figure 6: Stress-strain behaviour of pillars (Gale, 2018)**

High lateral confinement stress will be generated within the pillars with a sufficiently large w/h ratio (Kim and Larson, 2021), which will reduce the pillars' bursts risk and intensity. The test results in this study also indicated that coal samples with a larger w/h ratio will have ductile failure without severe bursts. Prassetyo divided the pillar into several different failure zones depending on the post-failure status to identify the burst area of pillars as shown in **Figure 7** (Prassetyo, 2011). The rib zone has severe failure such as particle ejection due to the presence of the free surface. Prassetyo *et al* found that the percentage of rib zone remains steady once the w/h ratio of the pillar is larger than 8 (Prassetyo et al., 2011), which means that the burst area will not have a significant increase when the w/h ratio is beyond 8.

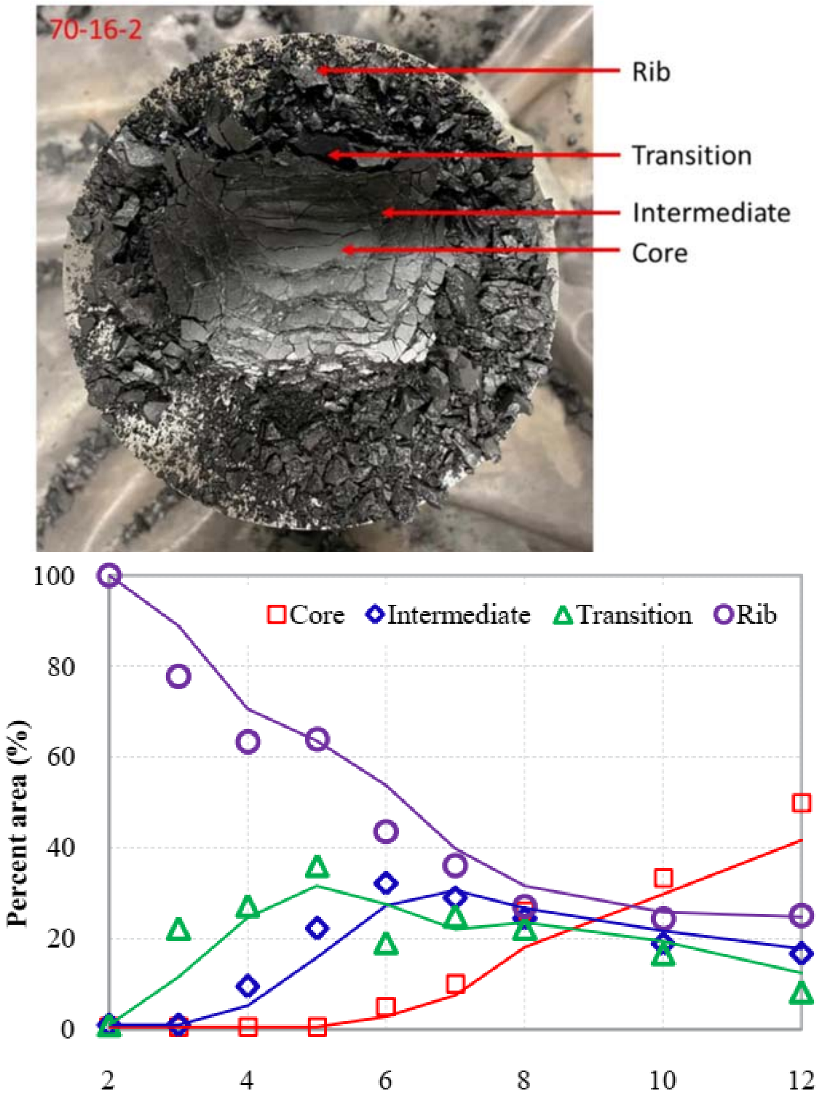



**Figure 7: The failure zones of coal samples at each w/h ratio (Prassetyo et al., 2011)**

**Critical w/h Ratio and FoS**

The Australia and South Africa pillar collapse databases (Hill, 2005) are suggestive that pillars with a higher w/h ratio are less likely to fail at a given FoS than pillars with a low w/h ratio (**Figure 8**). It should be noted that, while there are significantly more stable cases under the Limit Envelope than there are failed cases, i.e. being under the envelope does not mean a pillar will fail, being above the Limit Envelope means that there is no known precedent for such pillars ever having failed. This raises the possibility that pillars with a sufficiently large w/h ratio could meet the design functions of the pillars at lower FoS values, thereby reducing the coal reserves locked up in pillars and increasing development production rates. Understanding the post-peak behaviour of pillars at various w/h ratios is critical if pillar design is to use this approach, hence, future research, both in the laboratory and in the field, should be aimed at improving this knowledge.

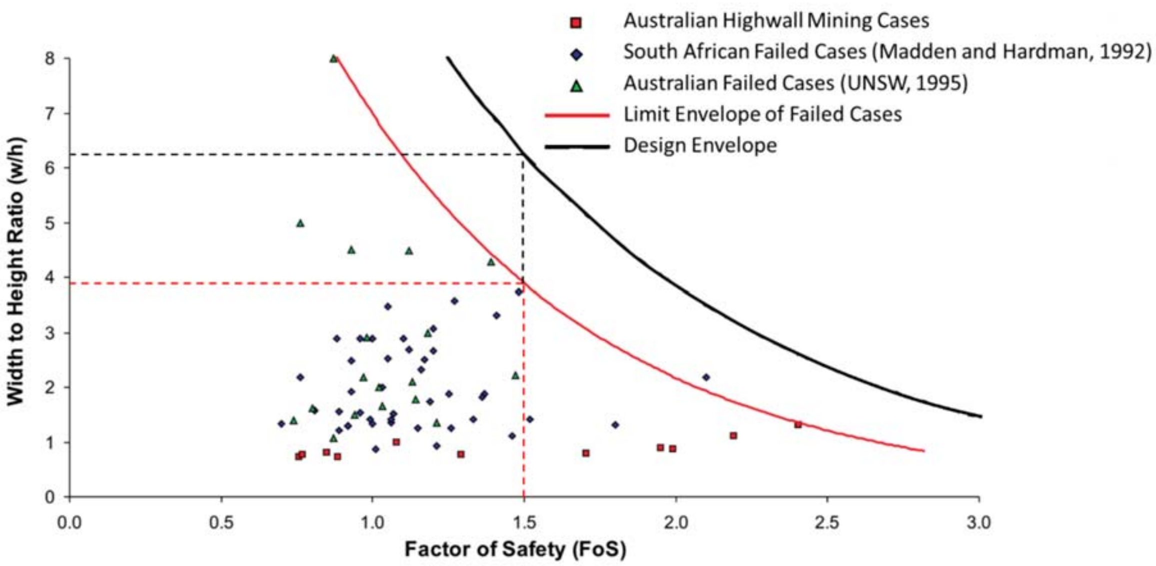



**Figure 8: Pillar collapses cases with different w/h ratio and FoS (Hill, 2005)**

## CONCLUSIONS

Coal pillars are to be subject to increasing geo-stress due to increased mining activities in deep coal seams. The increased vertical stress will lead to potentially oversized coal pillars or inadequate FoS. In this paper, the critical w/h ratio of coal pillars to maintaining the pillars stability with a smaller FoS is discussed. The uniaxial compression tests of square coal samples with different thicknesses were tested to reveal the strength and failure behaviours of coal samples with different w/h ratios. An obvious brittle-ductile transmission of coal samples with the increasing w/h ratio can be observed from the failure process.

Previous research also suggested that the pillar w/h ratio will achieve the maximized benefits at 4-6. The burst area of the pillar rib will not have a significant increase when the w/h ratio is beyond 8. However, the critical w/h ratio for coal pillars with a real size needs more evidence with further study as the results are still based on laboratory studies of limited coal seams. In the next stage, more uniaxial and biaxial compression tests of larger-sized coal samples with different w/h ratios need to be performed to confirm the critical w/h ratio. Based on the tested coal mechanical parameters, the numerical simulation of coal pillars with difference w/h ratios can be adopted to further reveal the stress and strain energy concentration within the coal pillars.

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