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STRENGTH CHARACTERISTICS OF ROOF ROCK-COAL COMPOSITE SAMPLES WITH DIFFERENT HEIGHT RATIOS UNDER UNIAXIAL LOADING

CHARAKTERYSTYKA WYTRZYMAŁOŚCIOWA PRÓBEK KOMPOZYTOWYCH SKŁADAJĄCYCH SIĘ Z WARSTW WĘGLA I MATERIAŁU SKALNEGO O RÓŻNEJ WYSOKOŚCI POD WPŁYWEM OBCIĄŻEŃ JEDNOOSIOWYCH

An uniaxial compression mechanical model for the roof rock-coal (RRC) composite sample was established in order to study the effects of height ratio of roof rock to coal on the structural strength of composite sample. The composite sample strengths under different height ratios were established through stress and strain analysis of the sample extracted from the interface. The coal strength near the interface is enhanced and rock strength near the interface weakened. The structural strength of composite sample is synthetically determined by the strengths of rock and coal near and far away from the interface. The area with a low strength in composite sample is destroyed firstly. An analytical model was proposed and discussed by conducting uniaxial compression tests for sandstone-coal composite samples with different height ratios, and it was found that the structural strength and elastic modulus decrease with a decrease in height ratio. The coal strengths far away from the interface determine the structural strengths of composite sample under different height ratios, which are the main control factor for the structural strength in this test. Due to its lowest strength, the rock near the interface first experienced a tensile spalling failure at the height ratio of 9:1, without causing the structural failure of composite sample. The coal failure induces the final failure of composite sample.

Keywords: strength characteristics, roof rock-coal (RRC) composite sample, height ratio of roof rock to coal, RRC interface, uniaxial compression test

Model mechaniczny modelu stropu w postaci próbek kompozytowych składających się z węgla i materiału skalnego pod działaniem obciążeń jednoosiowych został opracowany w celu zbadania wpływu stosunku wysokości warstwy stropu skalnego do warstwy węgla na wytrzymałość próbki kompozytowej. Wytrzymałość na ściskanie próbek kompozytowych dla różnych wielkości stosunku wysokości warstw określono na podstawie badania naprężeń i odkształceń próbek pobranych ze strefy kontaktu węgiel-skała. Wytrzymałość węgla w pobliżu strefy kontaktowej wzrasta podczas gdy wytrzymałość warstwy skalnej w tym rejonie jest zredukowana. Wytrzymałość próbki kompozytowej określana jest poprzez analizę wytrzymałości warstw węgla i warstw skały w pobliżu a także w pewnej odległości od strefy kontaktowej. W pierwszej kolejności

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zniszczeniu ulegnie część próbki kompozytowej o zmniejszonej wytrzymałości. Zaproponowano model analityczny i przeprowadzono dyskusję wyników otrzymanych na podstawie testów ściskania jednoosiowego próbki składającej się z węgla i piaskowca o różnym stosunku wysokości ich warstw. Stwierdzono, że wytrzymałość oraz wartość modułu sprężystości maleje wraz z malejącym stosunkiem wysokości warstw. Wytrzymałość węgla w znacznej odległości od strefy kontaktowej determinuje całkowitą wytrzymałość próbki kompozytowej dla różnych stosunków ich wysokości, a stosunek wysokości ich warstw okazuje się być głównym czynnikiem decydującym o wytrzymałości próbki. Z uwagi na najniższą wytrzymałość, warstwa skalna zalegająca najbliżej strefy kontaktu w pierwszej kolejności podległa rozwarstwieniu wskutek rozciągania, przy stosunku wysokości warstw 9:1, nie powodując jednak uszkodzenia próbki kompozytowej. Uszkodzenie warstwy węgla z kolei, prowadzi do całkowitego zniszczenia próbki kompozytowej.

Słowa kluczowe: charakterystyka wytrzymałościowa, strop modelowany jako próbka kompozytowa węgla i materiału skalnego, stosunek wysokości warstwy węgla do skały, strefa kontaktowa, test ściskania jednoosiowego

1. Introduction

In order to ensure the safe and efficient mining of coal resources, a large number of coal pillars need to be left around the mining space, including the strip coal pillar, section coal pillar, waterproof coal pillar and coal pillar for fault protection, etc (Chen et al., 2014; Chen et al., 2016; Singh et al., 2011; Liu et al., 2015; Liu et al., 2018; Zhao et al., 2019). These coal pillars act as support, boundary and isolation, etc. However, the composed structure of these coal pillars and their overlying strata constitute an important role in the safety of the mining space. Therefore, it is of great importance to study the mechanical properties of composed structure consisted of coal pillar and roof rock.

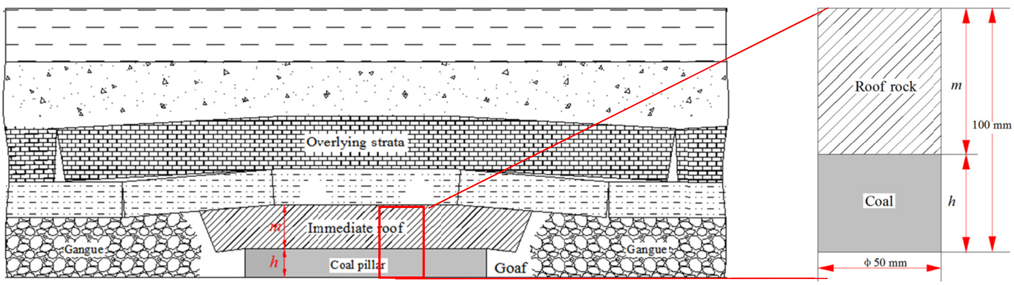
The strength is the basic mechanical property of the material. For studying the strength characteristics of composed structure consisted of coal pillar and roof rock, different interbedded cases between coal pillar and roof rock exist in coal mining, which were generally simplified as a composite sample consisted of roof rock and coal with bonded or frictional interface to form an integrated body in the laboratory tests or numerical simulation test. Many interesting results have been achieved. The effects of loading rates on the strength of a roof rock-coal (RRC) composite sample with a height ratio of 1:1 were studied by Yin et al. (2018a) and Chen et al., (2019). The results show that with a decrease in loading rate, the uniaxial compressive strength (UCS) of composite sample decreases. However, when the loading rate was 1×10^{-5} mm/s, the UCS showed an increasing trend. Also they analyzed the effects of joint angle in coal on the UCS of a RRC composite sample using PFC^{2D} software (Yin et al., 2018b). The strength characteristics of a RRC composite sample under various loading conditions were discussed and analyzed by Zuo et al. (2011a; 2011b; 2011c), including the uniaxial compression, tri-axial compression and cyclic loading and unloading. The effects of roof rock strength on UCS of a roof rock-coal-floor rock (RRCFR) composite sample were investigated by Liu et al. (2015). They found the structural strength of composite sample was mainly determined by the coal strength instead of rock strength. And the splitting fracture in coal can propagate to the roof stratum with a low strength. Poulsen et al. (2014) analyzed the strength reduction of a coal pillar due to water saturation embedded in a RRCFR composite sample. Based on the strain energy equivalent principle, the compression-shear strength criterion for the RRC composite sample were established and analyzed by Zhao et al. (2015) considering interface effect. Through the tests and numerical simulations using PFC^{2D} software and RFPA^{2D} software, the effects of interface angle between the roof rock and coal on the structural strength of a RRC composite sample were analyzed (Zhao et al., 2016; Guo et al., 2011).

The aforementioned studies are important for understanding the strength characteristics of RRC composite samples. Generally, the structural strength of composite sample is mainly determined by the mechanical properties of coal and roof rock, and the cementing properties between them. In practical engineering, the height of roof rock is often larger than that of the coal pillar. The height ratio of roof rock to coal affects the strength characteristics of composite sample. However, there are few studies on the effects of height ratio on the strength characteristics of a RRC composite sample. Chen et al. (2017) analyzed the mechanical characteristics and progressive failure mechanism of RRC composite samples with different height ratios using the acoustic emission (AE) monitoring technique and digital video camera monitoring.

In this paper, an uniaxial compression mechanical model for the RRC composite samples with different height ratios of roof rock to coal was established and analyzed. The proposed mechanical model was discussed by carrying out laboratory test for roof sandstone-coal composite samples with different height ratios. Also, the effects of height ratio on the structural strength of composite sample were analyzed.

2. Problem formulation

Collapse, rupture, separation and bending typically occur in the overlying strata from the bottom to the top when the coal seam on both sides of the coal pillar is mined. The immediate roof collapses, forming smaller gangue in the goaf area. Finally, the composed structure of roof rock and coal pillar is formed as shown in Fig. 1(a). The composed structure plays an important role in the safety of the mining operations. In order to study the strength characteristics of composed structure, the standard composite sample (φ 50 mm×100 mm) consisted of coal and roof rock is prepared for the laboratory test or numerical simulation test, as shown in Fig. 1(b).



(a) Composed structure (b) Laboratory or numerical test model

Fig. 1. Composed structure, laboratory or numerical test model of roof rock-coal pillar structure body

In Fig. 1, *m*, *h* are the heights of immediate roof rock and coal pillar, respectively. The relationship between *m* and *h* is (Chen et al., 2016; Tan et al., 2007)

$$m = \frac{h}{K-1} \tag{1}$$

Where *K* is the bulk factor of the caving immediate roof rock.

Thus,

$$\Delta_{mh} = m - h = \left(\frac{1}{K-1} - 1\right)h \tag{2}$$

The value of K is related to the mechanical properties and failure forms of immediate roof stratum. Generally, when the immediate roof stratum is sandstone with a high strength and more developed joints and cracks or when forced caving in immediate roof of hard sandstone, K is taken as between 1.3 and 1.35. When the strength of immediate roof stratum is relatively low (siltstone, shale, etc.), K is between 1.25 and 1.35 (Tan et al., 2007). The above values of K can be used if the collapse of immediate roof stratum is developed from its bending and caving. If the immediate roof stratum fails in a form of overall cut-off and collapse, K may be taken as 1. According to Eq. (2), $\Delta_{mh} = \infty$, means collapse occurs in the overlying strata from the bottom to hard stratum or surface.

In general, $m > h$, and thus $\Delta_{mh} > 0$. However, the researches of strength characteristics of RRC composite samples generally take m same as h. Instead, one must consider the height ratio effects on the strength characteristics of composite sample.

3. Mechanical model of RRC composite sample

A mechanical model is established for RRC composite sample under uniaxial compression, as shown in Fig. 2(a). The mechanical model satisfies the following assumptions: 1) Roof rock and coal are isotropic homogeneous bodies; 2) The strengths of rock and coal are governed by

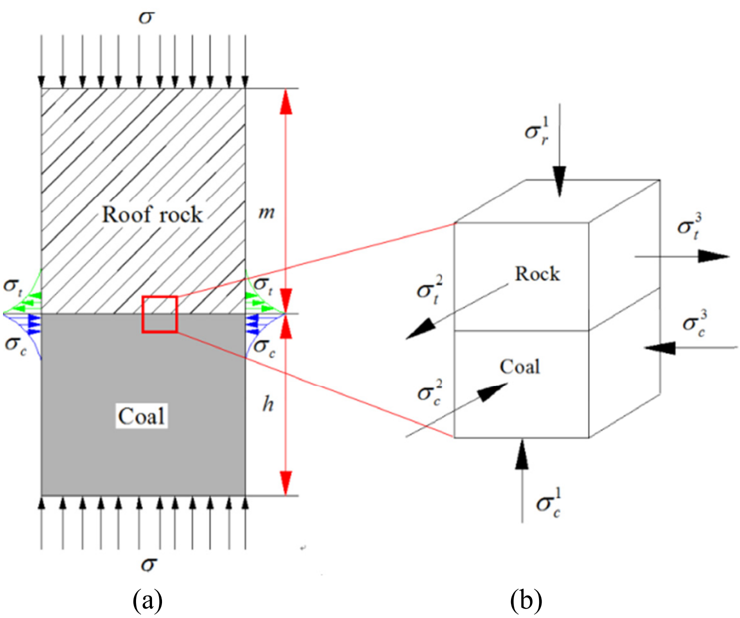


Fig. 2. Mechanical model of RRC composite sample

the Coulomb-Mohr yield criterion. The elastic moduli of roof rock and coal are E_r and E_c, and Poisson ratios are u_r and u_c, respectively. Suppose $E_r > E_c$, $u_r < u_c$, and the compressive stress is positive. There is no relative displacement on the interface between roof rock and coal under axial stress. Thus, due to the difference in the elastic moduli and Poisson's ratios of roof rock and coal, the lateral deformation of coal near the interface is limited in a certain extent by the roof rock. While, the lateral deformation of roof rock near the interface is enhanced by the coal. A tensile stress of σ_t for roof rock and a compressive stress of σ_c for coal are generated near the interface (Yin et al., 2018a). $\sigma_t = \sigma_c$, but their directions are opposite and they decrease rapidly from the outer boundary of the sample to its center. Due to the variation of the stress distribution near the interface, a three-dimensional representative model considering the zones near interface are taken for analyzing the strength of roof rock-coal composite materials sample, as shown in Fig. 2(b) (Chen et al., 2017). In Fig. 2(b), σ_t^2 and σ_t^3 are tensile stresses of roof rock in two horizontal directions, respectively, and σ_c^2 and σ_c^3 are compressive stresses of coal in two horizontal directions, respectively. σ_r^1 and σ_c^1 are the axial stresses for roof rock and coal, respectively.

According to the static equilibrium and superposition principle, the stresses and strains on each element surface should satisfy the following relationship (Tan et al., 1994):

$$\begin{cases} \sigma_c^1 = \sigma_r^1 = \sigma \\ -\sigma_t^2 = -\sigma_t^3 = \sigma_c^2 = \sigma_c^3 \\ \varepsilon_r^2 = \varepsilon_r^3 = \varepsilon_c^2 = \varepsilon_c^3 \end{cases} \tag{3}$$

Where ε_r^2 and ε_r^3 are the strains of coal in two horizontal directions, respectively, and ε_c^2 and ε_c^3 are the strains of coal in two horizontal directions, respectively.

The strains on each element surface are calculated as follows using the generalized Hooke's law (Tan et al., 1994):

$$\begin{cases} \varepsilon_r^2 = \dfrac{1}{E_r}\left[-\sigma_t^2 - u_r(\sigma_r^1 - \sigma_t^3)\right] \\ \varepsilon_c^2 = \dfrac{1}{E_c}\left[\sigma_c^2 - u_c(\sigma_c^1 + \sigma_c^3)\right] \\ \varepsilon_r^3 = \dfrac{1}{E_r}\left[-\sigma_t^3 - u_r(\sigma_r^1 - \sigma_t^2)\right] \\ \varepsilon_c^3 = \dfrac{1}{E_c}\left[\sigma_c^3 - u_c(\sigma_c^1 + \sigma_c^2)\right] \end{cases} \tag{4}$$

By combination of Eqs. (3) and (4), the stresses on each element surface are

$$\begin{aligned} -\sigma_t^2 = -\sigma_t^3 = \sigma_c^2 = \sigma_c^3 &= \frac{E_e u_c - E_c u_r}{E_r(1-u_c) + E_c(1-u_r)}\sigma \\ &= \frac{E_e u_c - E_c u_r}{E_r(1-u_c) + E_c(1-u_r)}\sigma_c^1 = \frac{E_e u_c - E_c u_r}{E_r(1-u_c) + E_c(1-u_r)}\sigma_r^1 \end{aligned} \tag{5}$$

Assume that the rock and coal near the interface are in the limit equilibrium state, total stresses of rock and coal near the interface are established by Mohr strength theory:

$$\begin{cases} \sigma_r^1 = -\dfrac{1+\sin\varphi_r}{1-\sin\varphi_r}\sigma_t^3 + \sigma_r \\ \sigma_c^1 = \dfrac{1+\sin\varphi_c}{1-\sin\varphi_c}\sigma_c^3 + \sigma_c \end{cases} \tag{6}$$

Where σ_r and σ_c are the uniaxial compressive strengths for rock and coal, respectively. φ_r and φ_c are the internal frictional angle for rock and coal, respectively.

Thus, σ_1^r and σ_1^c can be obtained by combination of Eqs. (5) and (6):

$$\begin{cases} \sigma_r^1 = \dfrac{\sigma_r}{1+\dfrac{1+\sin\varphi_r}{1-\sin\varphi_r}\dfrac{\lambda_1}{\lambda}} \\ \sigma_c = \dfrac{\sigma_c}{1-\dfrac{1+\sin\varphi_c}{1-\sin\varphi_c}\dfrac{\lambda_1}{\lambda}} \end{cases} \tag{7}$$

Where,

$$\begin{cases} \lambda = (\dfrac{E_r}{E_c}+1)^2 - u_c^2(\dfrac{E_r}{E_c}+\dfrac{u_r}{u_c})^2 \\ \lambda_1 = u_c(\dfrac{E_r}{E_c}-\dfrac{u_r}{u_c})\left[u_c(\dfrac{E_r}{E_c}+\dfrac{u_r}{u_c})+\dfrac{E_r}{E_c}+1\right] \end{cases}$$

Strengths of the roof rock and coal far away from the interface are confirmed by employing the Coulomb-Mohr yield criterion (Zhao et al., 2014):

$$\begin{cases} \sigma_{rf}^1 = -\dfrac{1+\sin\varphi_r}{1-\sin\varphi_r}\sigma_t^3 + \sigma_r \\ \sigma_{cf}^1 = \dfrac{1+\sin\varphi_c}{1-\sin\varphi_c}\sigma_c^3 + \sigma_c \end{cases} \tag{8}$$

Where σ_{rf}^1 and σ_{cf}^1 are the UCS for roof rock and coal far away from the interface, respectively. And the roof rock and coal far away from the interface are under uniaxial loading, thus,

$$\begin{cases} \sigma_{rf}^1 = \sigma_r \\ \sigma_{cf}^1 = \sigma_c \end{cases} \tag{9}$$

Therefore, the variation of the coal strength near the interface compared with the coal strength far away from the interface is

$$\Delta\sigma = \sigma_c^1 - \sigma_{cf}^1 > 0 \tag{10}$$

And the variation of the roof rock strength near the interface compared with the roof rock strength far away from the interface is

$$\Delta\sigma = \sigma_r^1 - \sigma_{rf}^1 < 0 \tag{11}$$

According to Eqs. (10) and (11), it can be seen that the coal strength near the interface is enhanced, higher than that of coal far away from the interface. The roof rock strength near the interface is weakened, less than that of roof rock far away from the interface. Moreover, the change of strengths is related to the elastic moduli and Poisson ratios of roof rock and coal.

The strengths of roof rock and coal far away from the interface can be taken as the strengths of single roof rock and coal samples with same size (Zuo et al., 2011a; Chen et al., 2017). Generally, the single standard rock and coal samples with φ 50 mm×100 mm can be achieved by the laboratory tests. σ_{rf}^1 and σ_{cf}^1 are confirmed by the size effect equation (Zuo et al., 2011a):

$$\begin{cases} \sigma_{rf}^1 = \dfrac{\sigma_{sr}(7+2\frac{D}{m})}{8} \\ \sigma_{cf}^1 = \dfrac{\sigma_{sc}(7+2\frac{D}{h})}{8} \end{cases} \tag{12}$$

Where σ_{sr} is the strength of single standard roof rock sample (φ50 mm×100 mm). σ_{cr} is the strength of single standard coal sample. D is diameters of the roof rock and coal in composite sample, taken as 50 mm.

In the laboratory or numerical test model, m and h are added to 100 mm. Thus, Eq. (12) can be changed as

$$\begin{cases} \sigma_{rf}^1 = \dfrac{\sigma_{sr}(7+2\frac{D}{m})}{8} \\ \sigma_{cf}^1 = \dfrac{\sigma_{sc}(7+2\frac{D}{100-m})}{8} \end{cases} \tag{13}$$

In Eqs. (7), (9) and (12), it can be seen that the heights of coal and rock in composites sample affect σ_{rf}^1 and σ_{cf}^1, then influence σ_r^1 and σ_c^1. Under same conditions, with a decrease in height ratio, i.e, m decreases, σ_{rf}^1 and σ_r^1 increase. While, σ_{cf}^1 and σ_c^1 decrease.

In addition, the structural strength of RRC composite sample is synthetically determined by the strengths of σ_{rf}^1, σ_{cf}^1, σ_r^1 and σ_c^1, shown in the following Eq.,

$$\sigma_{rc} = F(\sigma_r^1, \sigma_c^1, \sigma_{rf}^1, \sigma_{cf}^1) \tag{14}$$

Where, σ_{rc} is the structural strength of composite sample; F is the influence functions of σ_{rf}^1, σ_{cf}^1, σ_r^1 and σ_c^1 on σ_{rc}.

In order to keep stability of the composite sample, the axial stress of σ carried by the composite sample should be less than the minimum value of σ_{rf}^1, σ_{cf}^1, σ_r^1 and σ_c^1. Otherwise, the area with a low strength in composite sample will be destroyed firstly. Based on the above analysis, the height ratio influences σ_{rf}^1, σ_{cf}^1, σ_r^1 and σ_c^1. Subsequently, the structural strength of composite sample is affected by the height ratio. In order to study the effects of height ratio on the structural strength of composite sample and verify the mechanical model accuracy, uniaxial compression tests were conducted on roof sandstone-coal composite samples with different height ratios, as follows.

4. Experimental procedure

4.1. Sample preparation

Due to the height of roof rock stratum is larger than that of coal pillar, the height ratios of the roof rock to coal in the composite samples are taken as 9:1, 8:2, 7:3 and 6:4 in the uniaxial compression test, as shown in Fig. 3. The roof rock and coal blocks originated from the Jining coal mine, and the roof rock is the sandstone. Firstly, with the core-drilling machine, the coal and sandstone samples with a diameter of 50 mm were cored along the direction perpendicular to the interface of coal and rock blocks. Using the sawing machine, coal and rock samples with required heights for tests were achieved. Then both ends of the coal and sandstone samples were polished by a stone grinding machine. Finally, the coal and roof sandstone samples are bonded together into a composite sample with cyanoacrylate adhesive according to previous studies (Yin et al., 2018a; Chen et al., 2017; Zuo et al., 2011a).

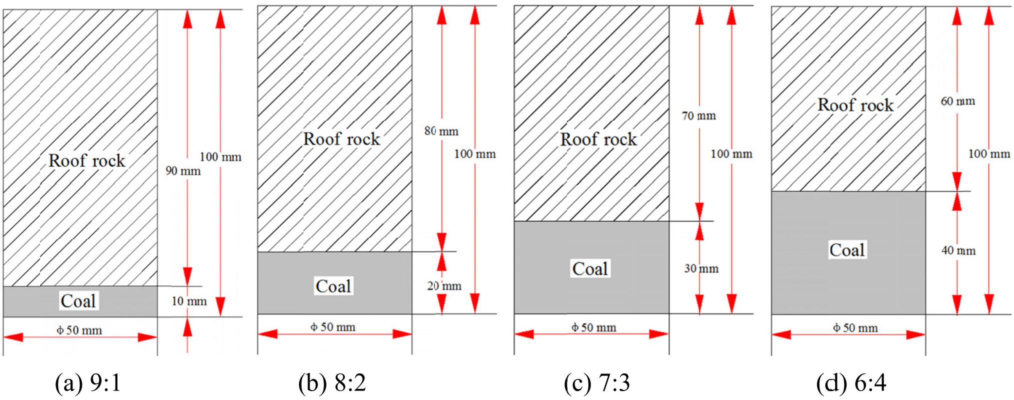


Fig. 3. Sketch map of RRC composite samples with different height ratios

4.2. Test equipment and methods

A Shimadzu AUTOGRAPH (AG-X250) in electronic universal testing machine was selected as the loading system. A double screw structure was adopted in the loading mode. The testing system could execute the conventional compression, tensile and other mechanical tests. The maximum loading could reach up to 250 kN. A displacement control loading method was adopted in the tests. For this work, the loading rate was set at 0.0005 mm/s.

4.3. Analysis and discussions on test results

Fig. 4 gives the stress-strain curves of uniaxial compression for roof sandstone-coal composite samples with different height ratios. In this test, σ_{sr}, E_r, u_r, φ_r of the single standard roof sandstone sample are 87.30 MPa, 8.13 GPa, 0.2 and 42°, respectively (Chen et al. 2017). The σ_{sc}, E_c, u_c, φ_r of the single coal sample are 29.24 MPa, 3.16 GPa, 0.3 and 30°, respectively. Therefore, according to the Eqs. (7), (9) and (12), the strengths of roof sandstone and coal near or far away from the interface are obtained, as shown in Table 1.

TABLE 1

Test results, strengths of roof sandstone and coal near or far away from the interface

Height ratio	σ_{rc} / MPa	σ_r^1 / MPa	σ_c^1 / MPa	σ_{rf}^1 / MPa	σ_{cf}^1 / MPa	Elastic modulus/GPa
9:1	62.09	41.92	183.26	88.51	62.14	7.00
8:2	42.12	42.64	129.36	90.03	43.86	4.80
7:3	38.51	43.56	111.39	91.98	37.77	4.27
6:4	36.14	44.79	102.41	94.58	34.72	3.75

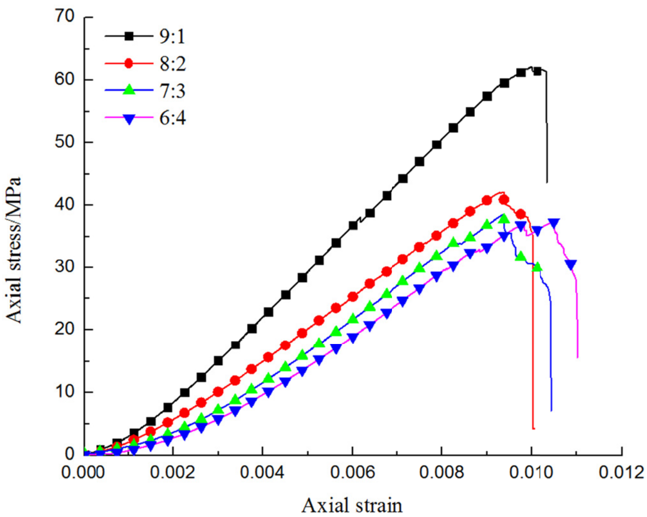
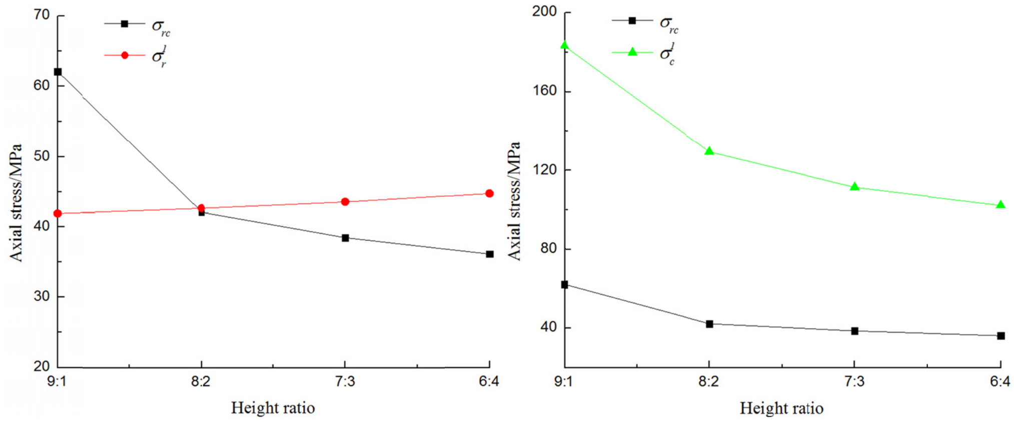
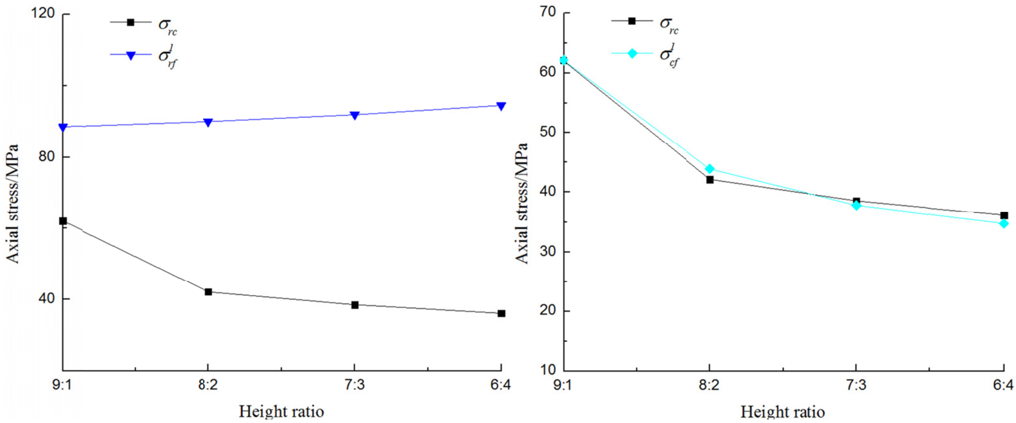


Fig. 4. Stress-strain curves of roof sandstone-coal composite samples with different height ratios

In Fig. 4 and Table 1, the structural strengths of composite samples with different height ratios are different, illustrating that the height ratio affects the structural strength of composite sample. The elastic modulus of composite sample decreases with a decrease in height ratio of roof sandstone to coal. The values of σ_r^1, σ_c^1, σ_{rf}^1 and σ_{cf}^1 vary widely under different height ratios. For further analyzing effects of height ratio on the structural strength of composite sample, Fig. 5 shows the relationships between σ_{rc}, σ_r^1, σ_c^1, σ_{rf}^1 and σ_{cf}^1.



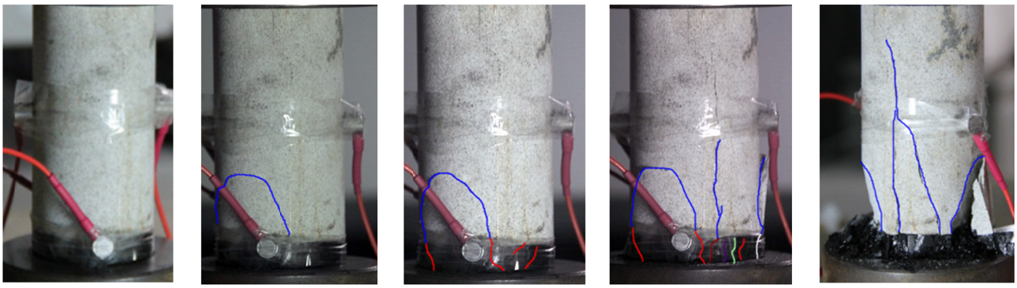
(a) Relationship between σ_{rc} and σ_r^1 (b) Relationship between σ_{rc} and σ_c^1



(c) Relationship between σ_{rc} and σ_{rf}^1 (d) Relationship between σ_{rc} and σ_{cf}^1

Fig. 5. Relationships between, σ_r^1, σ_c^1, σ_{rf}^1, σ_{cf}^1 and σ_{rc}

In Fig. 5, with a decrease in height ratio, the structural strength of composite sample decreases nonlinearly. σ_{rc} is the largest at 62.09 MPa with the height ratio of 9:1 and the least at 36.14 MPa with the height ratio of 6:4. Compared with σ_{rc} at the height ratio of 9:1, σ_{rc} at height ratios of 8:2, 7:3 and 6:4 decrease by 32.16%, 37.98% and 47.79%, respectively. The strength of coal near or far away from the interface decrease with a decrease of height ratio, agreeing with the variation trend of σ_{rc} with the height ratio, as shown in Fig. 5(b) and (d). While, the values of σ_c^1 at different height ratios are much higher than that of σ_{rc}, illustrating σ_c^1 is not the main control factor of the structural strength of composite sample. And the values of σ_{cf}^1 at different height ratios are basically accordant with that of σ_{rc}, illustrating σ_{cf}^1 is the main control factor of the structural strength of composite sample. Moreover, the decrease of σ_c^1 with a decrease of height ratio explains that the strength enhancement effect of interface restriction on the coal near the interface is reduced with the decrease of height ratio. In addition, the strength of rock near or far away from the interface increase with a decrease of height ratio, differing from the variation trend of σ_{rc} with the height ratio, as shown in Fig. 5(a) and (c). The values of σ^1_{rf} at different height ratios are much higher than that of σ_{rc}, indicating σ^1_{rf} is not the main control factor of the structural strength of composite sample. The values of σ^1_{rf} at height ratios of 8:2, 7:3 and 6:4 are larger than that of σ_{rc}, while σ^1_{rf} at height ratio of 9:1 is smaller than that of σ_{rc}. Thus, the rock near the interface is firstly destroyed in the progressive failure of the composite sample, as shown in Fig. 6 (Chen et al., 2017). In Fig. 6, it can be seen the rock near the interface first experienced a tensile spalling failure. This failure cannot cause the structural failure and instability of composite sample. The coal failure induces the final failure of composite sample. Also the increase of σ^1_r with a decrease of height ratio shows that the strength weakening effect of interface restriction on the rock near the interface is reduced with the decrease of the height ratio.



(a) (b) (c) (d) (e)

Fig. 6. Progressive failure of the composite sample at the height ratio of 9:1

According to above analysis, the coal strength near the interface mainly determines the structural strength of composite sample at different height ratios in this test. The calculated value of σ^1_{cf} at different height ratios by the analytical model are basically equal to that of the structural strength obtained by the uniaxial compression test, verifying the accuracy of the analytical model. The mechanical model can be used for analyzing the strength characteristics of RRC composite sample. It needs to be particularly pointed out, the structural strength of composite sample is also affected the interaction between roof rock and coal sample, and the initial defect in coal or roof rock. The coal strength far away from the interface can be considered to be the coal sample strength in the composite sample (Chen et al., 2017; Yin et al., 2018b). The axial compression deformation of the roof rock reduces the damage of axial stress on coal sample in the composite sample, which is equivalent to increase the coal strength (σ^1_c), then the structural strength increases. Meanwhile, the initial defect in coal decreases the coal strength and the corresponding structural strength is low. The value of σ_{rc} obtained by the laboratory test may be greater or less than that of σ^1_c achieved by the mechanical model.

5. Conclusions

In this paper, an uniaxial compression mechanical model for RRC composite samples with different height ratios is established and validated by carrying out laboratory test for roof sandstone-coal composite samples with different height ratios of roof rock to coal. And the effect of height ratio on the structural strength is analyzed. The following conclusions were achieved:

(1) The structural strength of composite sample can be synthetically determined by the strengths of rock and coal near and far away from the interface. The area with a low strength in composite materials sample is firstly destroyed. The coal strength near the interface is enhanced and rock strength near the interface weakened.

(2) The structural strength and elastic modulus of composite sample decrease with a decrease in height ratio. The coal strengths far away from the interface under different height ratios are related to the structural strengths, and they are the main control factor of the structural strength in this test. The mechanical model can be used for analyzing the strength characteristics of RRC composite sample.

(3) Due to its lowest strength, the rock near the interface first had a tensile spalling failure at height ratio of 9:1, without causing the structural failure of composite materials sample. The coal failure induces the final failure of composite sample.

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