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RESEARCH ON MINE SEAL STABILITY UNDER EXPLOSION LOAD AND GROUND PRESSURE IN UNDERGROUND COAL MINES

The mine seals in coal mines with a good impact resistance and air tightness are mainly used to isolate abandoned mining areas from active workings. For one thing, it can prevent the leakage of harmful gases, such as toxic gas from abandoned areas. For another, once an underground mine explosion happens, it can effectively block the spread of the explosion between the abandoned mining areas and the active workings. Hence, it is of great significance to study the explosion-proof performance and mechanical properties of the mine seals. First of all, the effect of slotting on the stability of the seals in coal mines under explosion load was explored in this study. By numerical simulations, the mechanical response characteristics of the seals with or without cutting a slot under the explosion load were compared in detail. The results show that slotting improved the stress concentration at the contact surface of surrounding rock by transferring partial impact received by mine seals to the surrounding rocks, thus, to achieve the effect of buffering explosion impact. Besides, such effect will be enhanced with increasing cutting depth into rock, and will stabilize when the depth is 20 cm. On this basis, the mechanical properties and damage of the seals constructed by different materials (standard brick and #C40 concrete) under the explosion load were compared. It was found that once a slot was set, the maximum deformation of the concrete seal was reduced, while the maximum deformation of the brick seal increased. Since the non-deformability of the concrete seal is obviously stronger than that of the brick seal, with the impact resistance stronger than that of the brick seal, the concrete seal is more suitable for slotting. Moreover, the damage of the seals in underground coal mines under the strata ground pressure was studied; the results of which show that the damage state under the ground pressure can be divided into 3 levels, i.e. no damage, minor damage and rapid development of damage. Meanwhile, it was found that the prestressed structure formed by the ground pressure at the level of no damage can enhance the protective effect of the seals in coal mines. However, when the ground pressure was further developed, the seal itself was destroyed and the

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protective effect was lost. In addition, the influence of roof to floor moving convergence, a deformation parameter of the roadway, on the seals was also investigated. The results show that the ground pressure and roof-to-floor convergence act on the seals in coal mines in the same way, thus roof to floor moving convergence can replace the ground pressure to analyze other related mechanical properties of the seals in coal mines in the future researches.

Keywords: Seals in underground coal mines; Numerical simulation; Slotting; Ground pressure; roof to floor moving convergence; damage level

1. Introduction

With a complex structure, the underground coal mining system is a space whose accident probability and consequence model is difficult to predict. Once an explosion occurs, there will be heavy casualties. Underground coal mine explosions are mainly caused by the following factors: The accumulation of flammable gases represented by coal gases (Zhang et al., 2019; Brune & Saki, 2017; Muduli et al., 2018; Wang et al., 2017), coal dust and secondary explosion caused by flammable residue in coal dust (Lin et al., 2019a; Yu et al., 2013). Extensive researches indicate that most underground coal mine explosions occur in abandoned mining areas, working faces and development heads (Lin et al., 2019b; Yan, 2016). Therefore, to ensure the safety of underground mines and to avoid economic damages, it is of great significance to explore the explosion-proof performance of mine seals in coal mines (H, 2014; Karacan, 2015) which are used to isolate abandoned mining area. For a long time, abundant researches have been carried out on the influences of various filling materials like Luokexiu foam (Ma, 2017) and polymer swelling molecules (Zou et al., 2015; Huang et al., 2014a; Huang et al., 2014b) on air tightness and ventilation resistance of seals in coal mines (Song et al., 2016; Cheng et al., 2019a; Sun & Pang, 2017). However, few researches focus on the concrete seal, the explosion-proof building materials or brick seal and there is no comparison of the ability of different materials to withstand explosion load. In terms of engineering, when constructing the seals in coal mines, it is necessary to slot on the surrounding rock of the roadway, and the cutting depth usually needs to reach the hard layer of rock so as to improve the stability of the seal and the surrounding rock. Nonetheless, such empirical measure lacks theoretical supports. Previous researches on the slotting of underground roadway (Liu et al., 2019; Wang et al., 2019; Zhang et al., 2019; He et al., 2015; Jing et al., 2017; Ti et al., 2018; Yuan et al., 2018; Cheng et al., 2017) mostly studied the blasting effect as well as the stress distribution and damage of the original rock at underground development faces. Only a few researches explored the slotting effects on seals in underground coal mines and they still failed to reveal the mechanical properties and damage mechanism of the seals under explosion load with and without slotting (Wang & Wang, 2019). Therefore, further analyses on interactions between surrounding rocks must be carried out. The ground pressure acting on the seals in coal mines is a physical quantity difficult to measure directly in the coal mine. Although many researches have attempted the derivation of the ground pressure equation (Lei et al., 2014; Cao et al., 2015; Liu 2017; Zhang 2018, Cheng et al., 2019b), most of them are often limited to a specific condition. Hence, they are not universal. Therefore, the roof-to-floor moving convergence is often considered a reference one to estimate the ground pressure, but there are no relevant research supports for applying this instead method. Hence, it is necessary to further explore the comparisons between using the roof-to-floor moving convergence and the ground pressure. In this study, the mechanical properties and damage mechanisms of the seals constructed by different materials (standard bricks and #C40 concrete) with or without slotting were compared under the explosion load. Besides, the stability of the seals with different slotting depths was tested to figure out the optimal slotting depth. The damage of the seals in coal mines by the ground pressure was studied and the relationship between the ground pressure and the roof-to-floor moving convergence was discussed, providing relevant theoretical support for designing mine seals in underground.

2. Numerical model

2.1. Modeling of mine seals

This study explored the typical design of an impact-resistant seal in Chines underground coal mines. Using the compound structure (Sun et al., 2019; Tarlochan et al., 2012), the seals in coal mines consists of three parts, i.e. the interior seal (the pressure bearing layer), the filling material layer and the exterior seal (protective layer). Both the interior and exterior seals are 0.75 m thick and the mixture filling material are the combination of loess and quicklime (the weight ratio is 9:1) with a thickness of 2 m filled in the middle section. Considering the needs to investigate the interaction between the seal, the surrounding rock, the roof and floor as well as the effect on the stability of seal, a computer based numerical model was established as shown in Figure 1. The

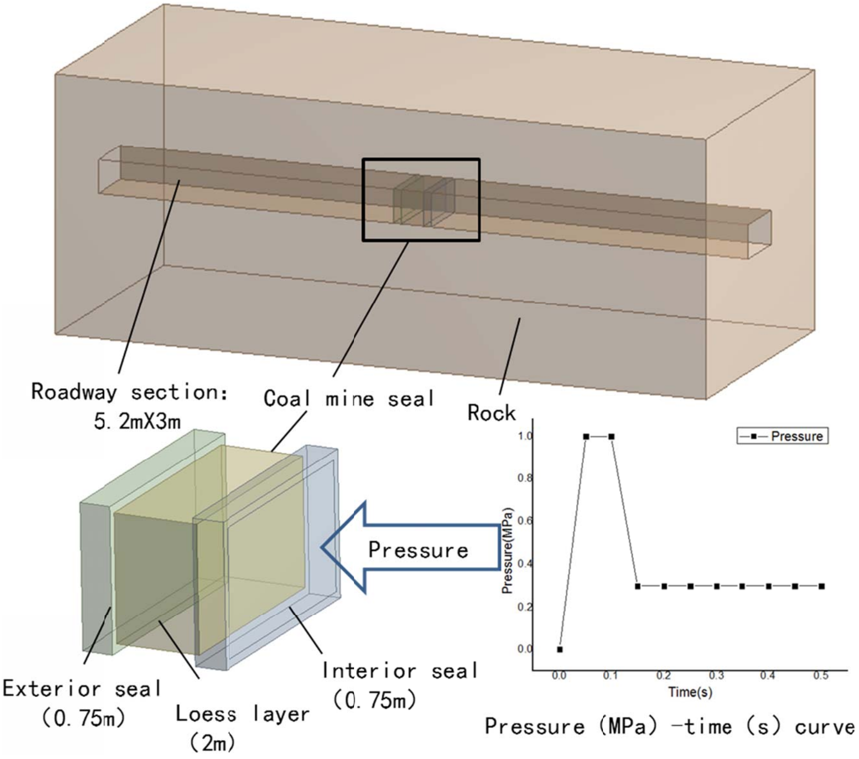


Fig. 1. Numerical model of compound seal

roadway's cross-section is 5.2 m×3 m and the length is 60 m. A rock stratum formation model was established around the roadway and its thickness was set as 10 m. The pressure-time curve used for the explosion load used in the numerical experiment was based on the Mine Safety and Healthy Administration (MSHA) regulations and a series of numerical impact simulation tests on the seals in coal mines were completed.

In numerical experiments, in order to investigate the response of the brick seal and #C40 (a symbol showing the compressive strength of such concrete is 40 MPa) concrete seal to the explosion impact, two experimental models of different interior and exterior materials were set up with maintaining other same parameters. The properties of the experimental materials are shown in Table 1.

TABLE 1

Properties of experimental materials

Name	Concrete	Brick	Filling (loess/ quicklime)	Rock
Density	2300 kg·m^{-3}	1800	1810 kg·m^{-3}	2600 kg·m^{-3}
Poisson's ratio	0.18	0.25	0.45	0.19
Young modulus	3E+10 Pa	3.02E+9 Pa	2.4E+7 Pa	2.07E+10 Pa
Tensile strength	2.39 MPa	0.87 MPa	—	—
Shear strength	2.68 MPa	1.04 MPa	—	—

3. Influence of slotting on mechanical properties of seal and surrounding rock under explosion load

3.1. Stress distribution and deformation of seal

3.1.1. Stress state and deformation of seal without slotting

To investigate whether the slotting has a positive effect on impact resistance of the seal under explosion load, with the seals constructed by different materials without slotting as the research object, the maximum deformation and stress distribution under the explosion load were sequentially analyzed, the results of which are shown in Figure 2.

When it comes to the deformation distribution, the deformation states of the concrete seal and the brick seal are similar, that is, the middle part of the interior seal is sunken with maximum deformation. The interior seal compresses the filling material layer, so that the stress distribution in the front part of the filling material layer is consistent with that at the back side of the interior seal, and the largest displacement is also found at the center of the filling material layer. From the perspective of the amount of deformation, the maximum deformation at the center of the concrete seal is 0.79 mm, and that of the brick seal is 3.50 mm; while the deformation of the exterior seal is not large, with the maximum deformation of the concrete exterior seal being only 0.036 mm and that of the brick exterior seal being about 0.250 mm. According to the above 2 sets of data, the concrete seal has a stronger non-deformability than the brick seal.

In terms of tensile stress, for the interior seal, stress concentration is likely to occur at the center of the back of the concrete seal and the 4 ridges on the front side, and the maximum tensile stress exceeds the strength limit, which might lead to some damage. The ridgelines on the

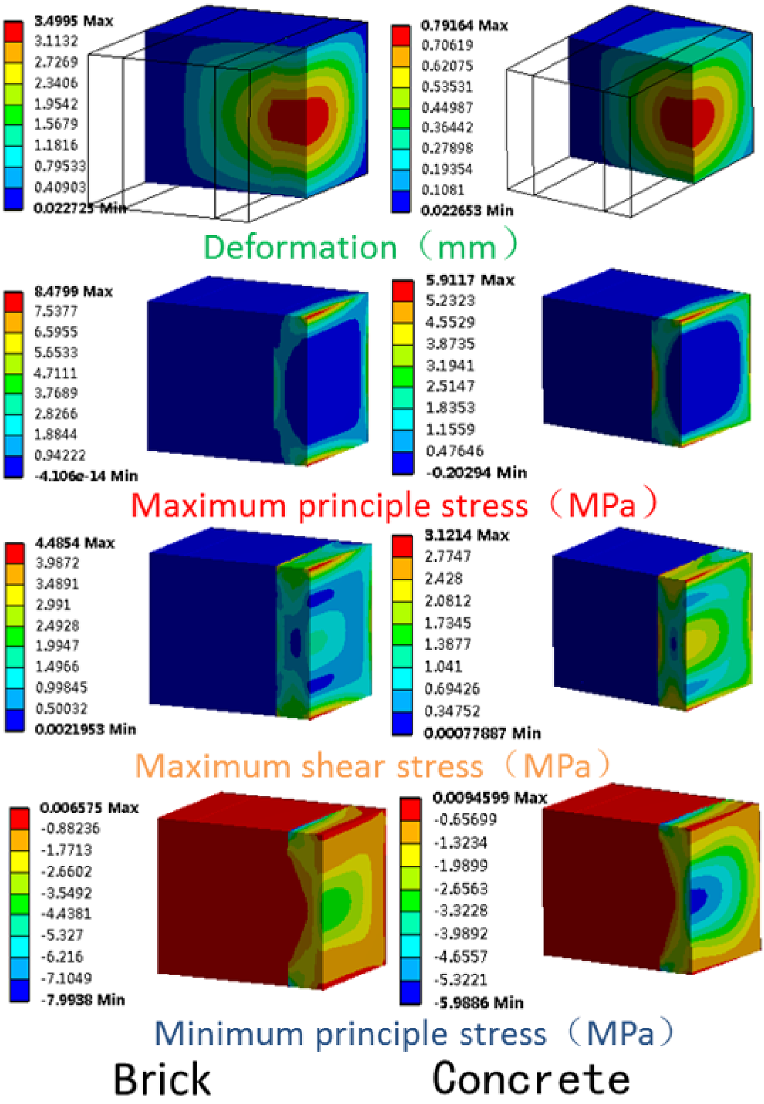


Fig. 2. Deformation and stress state of seal (Cutaway perspective)

front side of the brick seal are prone to stress concentration, and the maximum tensile stress far exceeds the strength limit, which might cause tensile stress damage. For the exterior seal, stress concentration is likely to occur at the 4 front ridges, but 0.26 MPa is not large for the concrete seal, and 0.55 MPa is also safe for the brick seal.

From the perspective of the numerical value, the maximum shear stress of the seals, i.e. 3 MPa and 4 MPa, exceeds the strength limit, so the interior seal will be damaged to some extent. In both cases, the maximum shear stress of the exterior seal is small, so the exterior seal is basically in a safe state.

The minimum principle stress of the seal is relatively high, but due to the strong compressive capacity of the 2 materials, the values are much lower than their compressive limits, so the influence of the minimum principle stress on the seal was not taken into consideration in the following experiments.

3.1.2. Stress state and deformation of seal with a slotting depth of 20 cm

Based on the above analysis on the seal without slotting, a control experiment on the seal with cutting depth of 20 cm as the research object was carried out to compare the stress distribution and deformation of the seal with and without slotting. The analysis results are shown in Figure 3.

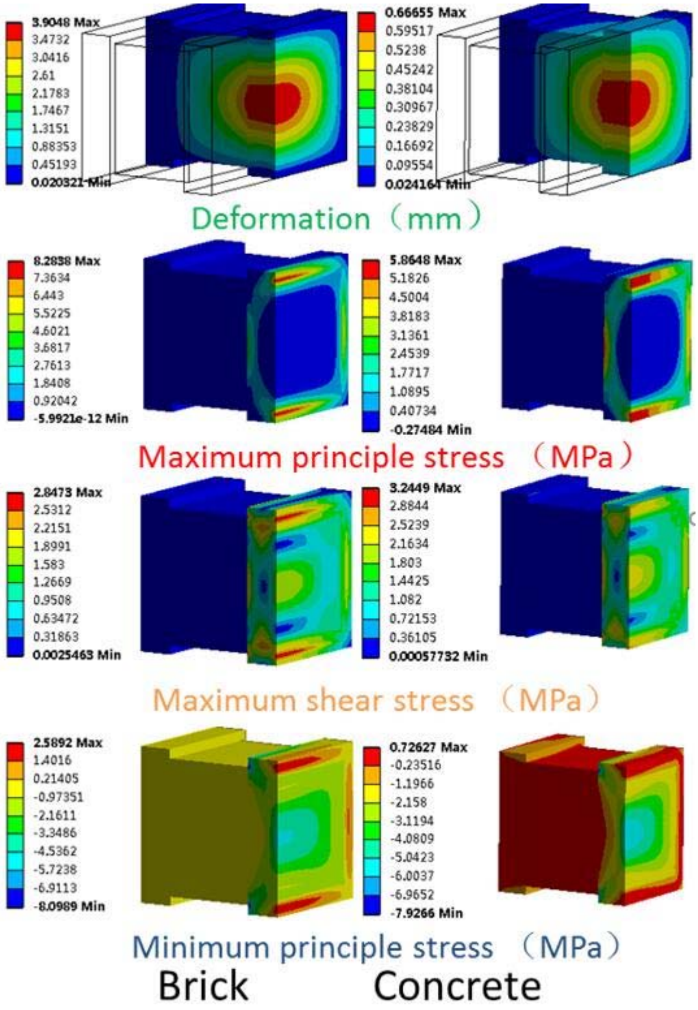


Fig. 3. Deformation and stress state of seal with a slotting depth of 20 cm (Sectional View)

The maximum deformation of the concrete seal after slotting is 0.79 mm and 0.66 mm, respectively. The maximum displacement of the brick seal without slotting and with a slotting depth of 20 cm is 3.4995 mm and 3.9048 mm, respectively. After slotting, the maximum deformation of the concrete seal is reduced, while that of the brick seal is increased, which shows that the concrete seal is more suitable for slotting than the brick seal. The deformation distribution of the concrete exterior seal has changed, with the maximum deformation transferred from the middle of the interior seal to the front end of the slotting, which indicates that slotting part is subjected to certain impact.

The distribution of tensile stress before and after slotting is basically consistent. There is a relatively high stress around the load face of the 2 types of seals, especially on the upper and lower sides, and the tensile stress is concentrated at the front end of the slotting, with the maximum value increased.

Without slotting, the high shear stress is mainly found on the 8 ridges in front of and behind the interior seal. The maximum shear stress appears on the back of the interior seal, while the stress on the exterior seal and the filling material layer is small. With a slotting depth of 20 cm, for the concrete seal, the maximum shear stress mainly occurs in the position where the back slotting compresses the rock layer; for the brick seal, a high shear stress is found on edge of its front load face.

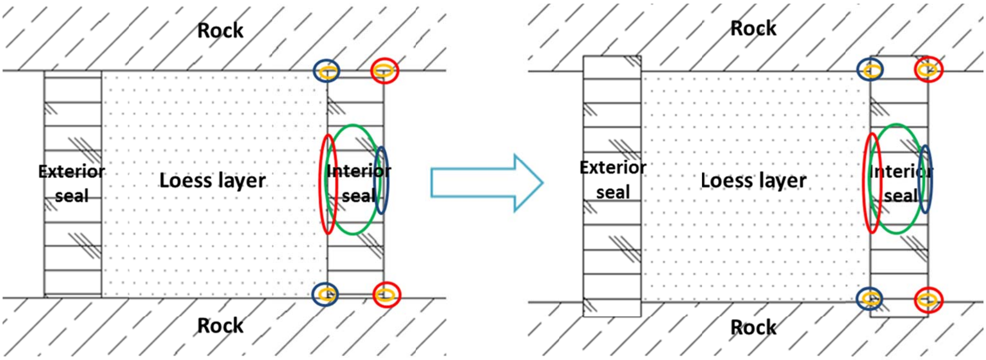
In general, under the explosion load, compared with the experimental results without slotting, the stress value of the seal with slotting slightly decreases, while the stress value of the surrounding rock increases as a whole, which indicates that the seal transfers more impact to the surrounding rock, and the bond between the seal and the surrounding rock is strengthened by the slot.

3.2. Stress concentration in seal and surrounding rock

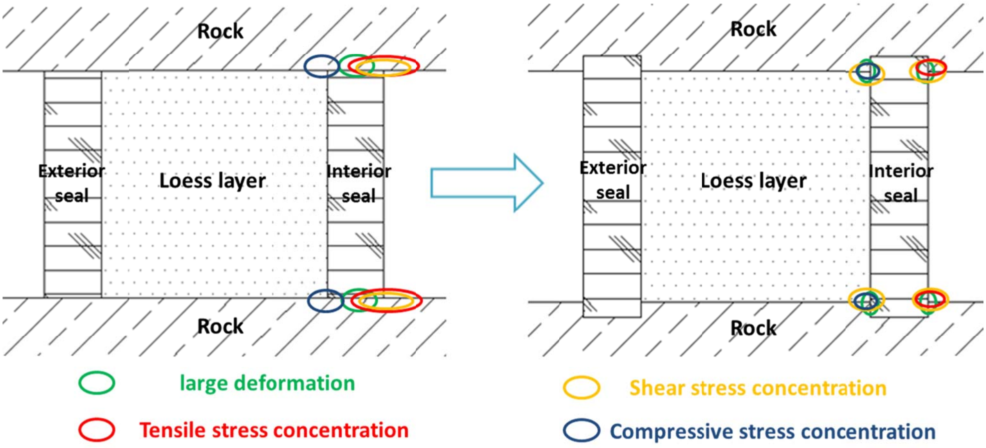
Figure 4 shows the stress concentration in the surrounding rock and the seal. The position of stress concentration in seal with and without slotting has not changed substantially. However, for stress concentration in rock, the position of maximum deformation and maximum shear stress has changed. It can be seen that the maximum displacement of the rock formation occurs at the upper and lower ends of the interior seal. When there is no slotting, the maximum deformation of the surrounding rock of the roadway occurs in the upper and lower rock layers in contact with the interior seal; with a slotting depth of 20 cm, the maximum deformation is found at the position where the slotting part is in contact with the back of the interior seal. When it comes to stress distribution, a large amount of concentrated stress is found on the contact surface of the seal and the rock layer, that is, the weak link of the stable structure, which is likely to damage the seal and lose the protective effect. After the slotting, the stress is not concentrated on the main weak plane, which is beneficial to reduce the damage.

3.3. Seal damage

To study the damage of seal with and without slotting, the tensile stress damage, shear stress damage and dangerous area of the seal were discussed respectively. Figure 5 shows the damage of seal without slotting and seal with a slot depth of 20 cm. According to the relating standard (Kallu, 2009), when the stress in a certain area exceeds 70% of the corresponding strength limit, the area is defined as a danger zone marked green. Otherwise, it is defined as a safety zone which



A comparison of stress concentration in seal with a cutting depth of 20cm and seal without cutting



A comparison of stress concentration in rock with a cutting depth of 20cm and seal without cutting

(a) Seal without slotting (b) Seal with a slot depth of 20 cm

Fig. 4. Comparisons of stress concentration in seal with slotting and seal without slotting

is marked blue. However, stress damage will occur on the area marked in red, as the stress increases beyond the standard strength limit. Without slotting, both the brick seal and the concrete seal is damaged in the interior part, while the exterior seal is not damaged. The damage of the concrete interior seal is mainly the tensile stress damage of the concrete at the back and front of the interior seal, which will invalidate the connection between the seal and the front end of the rock layer. The shear stress damage occurs on the back of the seal and the ridges of the seal. The brick seal is seriously damaged, with the tensile stress damage penetrating the seal and the shear stress damage extensively distributed in the seal.

With a slot depth of 20 cm, the damage of the seal is basically similar to that of the seal without slotting, but there are some differences. According to the tensile stress damage, damage of the concrete seal penetrates along the front sides, and the damage of seal with a slot depth of 20 cm is disconnected at the 4 corners. After slotting, the shear stress damage of the concrete

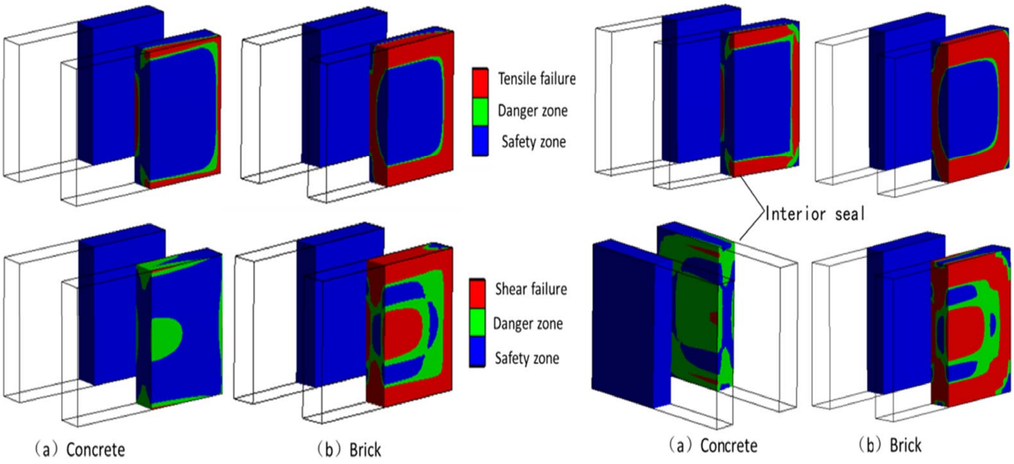


Fig. 5. Damage of seal without slotting (left) and seal with a slot depth of 20 cm (right)

interior seal is quite obvious at the position where back of the slotting compresses the rock formation; while the brick seal is still seriously damaged.

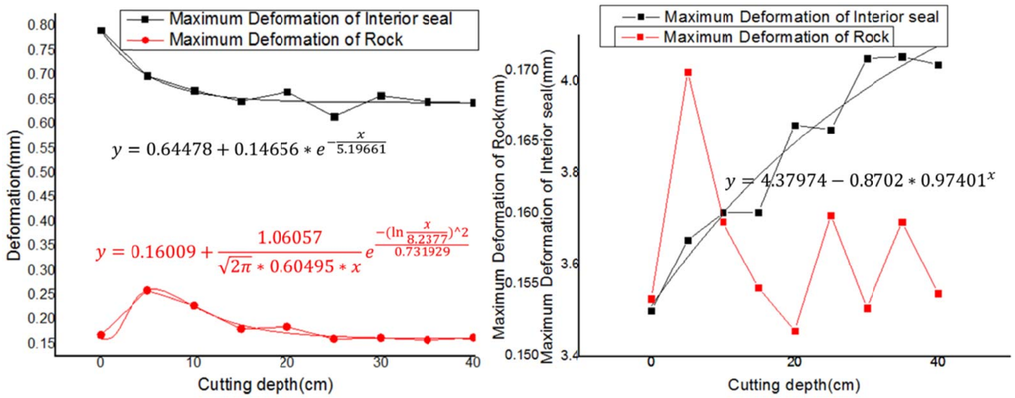
Generally speaking, the tensile stress and shear stress damage of the brick seal are much larger than those of the concrete seal. The concrete seal used in the experiment outperforms the brick seal in the protective effect. Besides, this compound construction guarantees the safety of the exterior seal under given conditions, but the safety can longer be ensured in the case of two or more explosions. The tensile stress and shear stress damage of the brick seal still are nearly 50%. It is considered that the damage of the interior seal is invalid and there is not much change.

3.4. Influence of slotting depth on stability of seals in coal mines under explosion load

The previous section explained the difference between the seal with slotting and without slotting, and the influence of the slotting depth would be explored in this section. The cutting depth was set to 0 cm, 5 cm, 10 cm, 15 cm, 20 cm and 25 cm. With parameters such as deformation and stress of the seal are selected as reference indexes. The results obtained are shown in Figures 6 and 7.

3.4.1. Variation of relative displacement of surrounding rock and seal with the slotting depth

To know how the relative displacement changes with the surrounding rock and seal, the simulation results are expressed in a broken line graph (Fig. 6), so as to display the variation trend. It can be seen that the maximum displacement of the concrete seal decreases at the initial stage without slotting. But the amount of change is not large, which is basically kept at about 0.65 mm. For the brick seal without slotting, as the slotting depth increases, the maximum displacement increases firstly and then is stabilized at about 4.0 mm. When it comes to the brick seal with slot-



(a) Concrete (b) Brick

Fig. 6. Variation of displacement of seal with the slotting depth

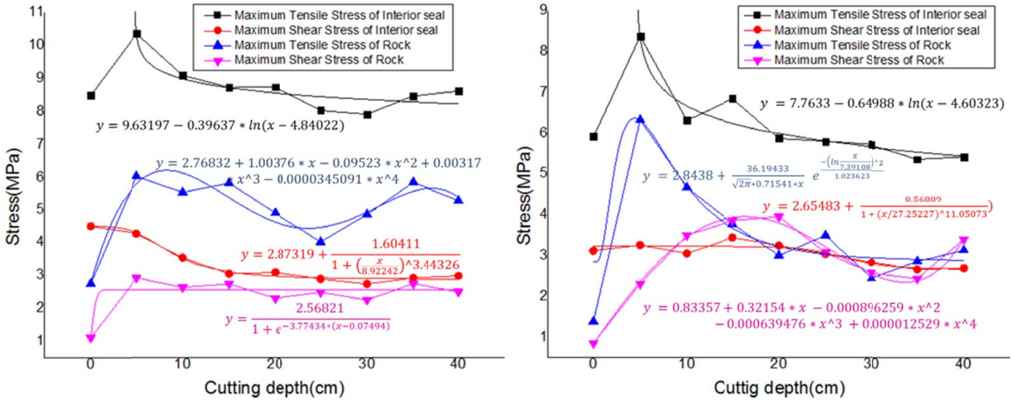
ting, with the maximum displacement increasing firstly and then decreases. With the slot depth increasing, the concrete seal has the strongest non-deformability, the surrounding rock features the intermediate non-deformability, and the brick seal has the weakest non-deformability. As a consequence, the concrete seal can better transmit the impact to the surrounding rock. Since the concrete seal transforms the impact into the rock, its displacement gradually decreases and then tends to be stable as the slotting depth increases. On the contrary, the brick seal cannot well transmit the impact into the rock, and the increase of the slotting depth leads to an increase in its area, resulting in an increase in the amount of deformation.

The maximum displacement of the surrounding rock constructed by the 2 materials varies similarly with the slotting. The maximum displacement of the surrounding rock increases in the early stage because the seal transmits part of the impact to the surrounding rock after slotting. Then, since the force transmission area increases as the slotting depth increases, the impact caused by the slotting to the surrounding rock is no longer concentrated in a small range. In other words, the slotting can transform the impact on the seal into the rock to a certain extent, and such effect will increase as the slotting depth increases. However, restricted by the stress transfer coefficient, such effect will gradually be weakened, and the maximum displacement of the rock will tend to be stable. As shown in the figure, as the slotting depth reaches 20 cm, the maximum displacement has basically been stable.

3.4.2. Variation of stress of seal with the slotting depth

As shown in Figure 7, as the slotting depth increases, the maximum tensile stress of the seal and surrounding rock increases sharply first, then decreases and becomes stable in the end. For the seal and surrounding rock after the slotting, the large tensile stress occurs on the contact surface of the interior seal at the slotting part, with the maximum tensile stress found at the ridges and corners (Figs 4 and 5). According to the fitting curve, the slotting depth should reach more than 20 cm to drop the tensile stress from the high stress zone to the stable stress zone.

On the one hand, the relative displacement between the surrounding rock and the seal decreases with the increase of the slotting depth, and it tends to be stable when the slotting depth



(a) Concrete (b) Brick

Fig. 7. Variation of stress of seal with the depth of the slotting

reaches 20 cm. On the other hand, as the slotting depth increases, the maximum tensile stress of the seal and the surrounding rock increases sharply first and then decreases. When the slotting depth reaches 20 cm, the tensile stress is transformed from the high stress zone to the stable stress zone. Based on the above experimental results, 20 cm is obviously the optimal slotting depth.

4. Influence of interaction between rock layers on seals in coal mines

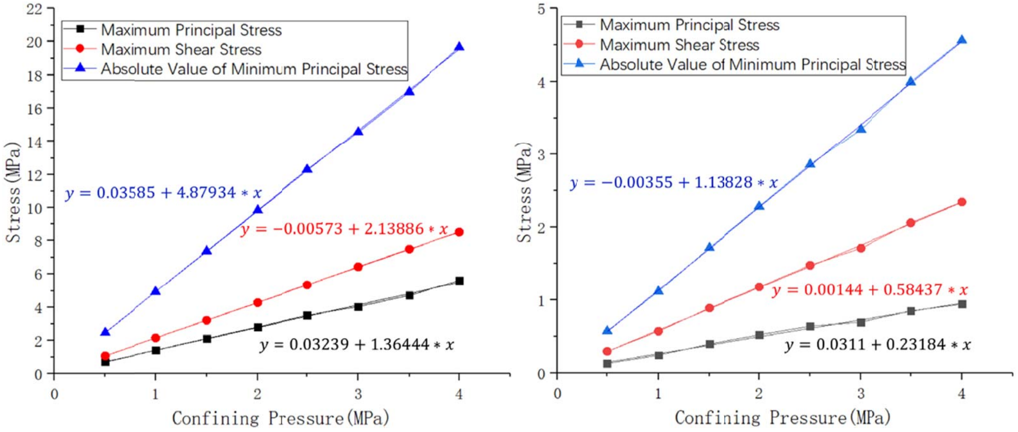
Changes in the ground pressure accelerate the deformation speed of the roadway in the underground mine, reduce the service life of the roadway and cause the roof fall accident. Once the seal is slightly damaged under the ground pressure, the sealing effect will definitely be reduced and the protective function may be considered invalid. To avoid such situation, it is necessary to consider whether the seal will be damaged when the ground pressure is applied. If yes, it is important to take strict precautions against the ground pressure. This study explores the stress distribution, deformation and damage of the seal underground pressure, as well as the relationship between the ground pressure and roof-to-floor moving convergence.

4.1. Influence of ground pressure on seal stability

In the experiment, the mine pressure was gradually increased. Altogether 8 experiments were carried out. For each experiment conducted, a ground pressure of 0.5 MPa was increased to observe the stress state and damage of the seal.

4.1.1. Stress state of seals in coal mines under ground pressure

Figure 8 shows how the stress values of the seal vary with the increase of the ground pressure. It is found that the variation of the stress of the concrete seal and brick seal is linearly correlated with the ground pressure. According to the above results, for the concrete seal, if the ground pressure increases averagely by 1 MPa, the maximum shear stress will increase by 2.1 MPa, the maximum compressive stress will increase by 4.9 MPa, and the maximum tensile stress will increase by 1.36 MPa; when it comes to the brick seal, if the ground pressure increases by 1 MPa on average, the maximum shear stress will increase by 0.58 MPa, the maximum compressive stress will increased 1.13 MPa, and the maximum tensile stress will increase by 0.23 MPa.



(a) Concrete (b) Brick

Fig. 8. Variation of seal stress with ground pressure

4.1.2. Seal Damage under ground pressure

Since the seal is only damaged by shear stress under the ground pressure, this experiment mainly studies the influence of ground pressure on the shear stress damage of the seal. The damage of the seal was analyzed with the ground pressure being 1 MPa, 2 MPa, 3 MPa and 4 MPa, respectively. Figure 9 shows the shear stress damage of the seal under different ground pressures. As mentioned above, blue represents the region where the stress is less than 70% of the strength limit, and green represents the area where the stress is greater than it. When the stress value increases beyond the limit, stress damaged can be considered to occur there, and it is marked in red.

As shown in the figure, there is no damage to the concrete seal at a ground pressure of 1 MPa, but there is a small amount of danger zone. When the ground pressure reaches 2 MPa, a large amount of damage has occurred. For the brick seal, the seal is completely in a safe state at a ground pressure of 1 MPa. As the ground pressure reaches 2 MPa, most of the seal is in a safe state, with only a small danger zone located on the exterior seal. At a ground pressure of 3 MPa, the danger zone can be found in most areas, and a small amount of damage is located on the exterior seal. As the ground pressure reaches 4 MPa, abundant damage occurs inside the seal. It can be thus seen that there is a certain gap between the concrete seal and brick seal in withstanding the ground pressure.

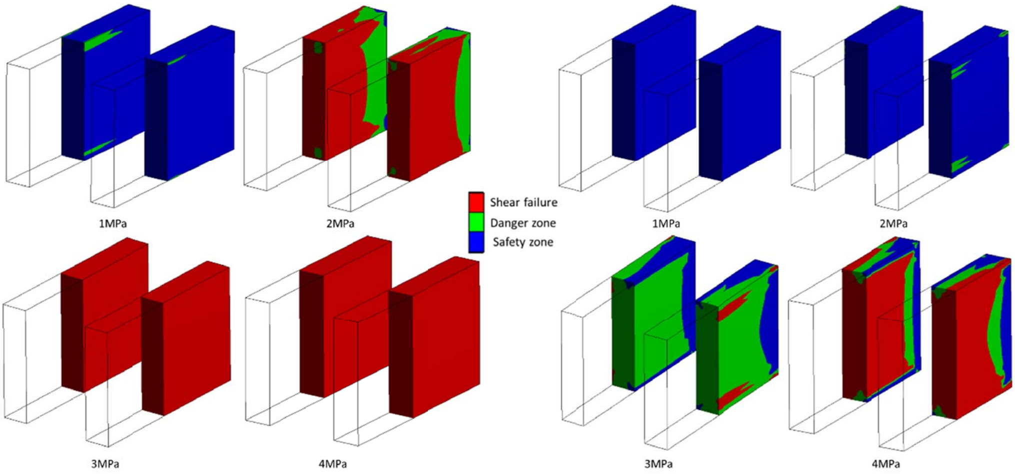


Fig. 9. Damage of seal under ground pressure

4.2. Effects comparisons by ground pressure and roof-to-floor moving convergence

Since it is difficult to directly measure the ground pressure acting on the seal in the mine, the roof-to-floor moving convergence is used as a reference value to estimate the ground pressure. However, there is no relevant research to support the principle of the method, so the relationship between the ground pressure and roof-to-floor moving convergence cannot be effectively explained. Hence, this study explores the influences of roof-to-floor convergence and ground pressure on the mechanical properties of the seal, as well as the relationship between the two.

4.2.1. Relationship between ground pressure and roof-to-floor moving convergence

It can be seen from Figure 10 that an increase of 1 MPa in the average ground pressure leads to an increase of 0.81 mm in the roof-to-floor moving convergence, while there is a certain deviation between the shrinkage of the seal and roof-to-floor moving convergence. This is especially the case when it comes to the concrete seal. Once completed, the seal will support the roadway (Chen et al., 2018), which will hinder the contraction. It should be noted that under the same ground pressure, the roadways of the concrete seal and the brick seal have almost the same roof-to-floor moving convergence.

4.2.2. Comparisons of concrete seal and brick seal damages

Once the seal is slightly damaged under the ground pressure, its sealing effect and protective function will be reduced. Therefore, damage to the seal should be avoided in underground mines as much as possible. In order to study the influence of the ground pressure and roof-to-

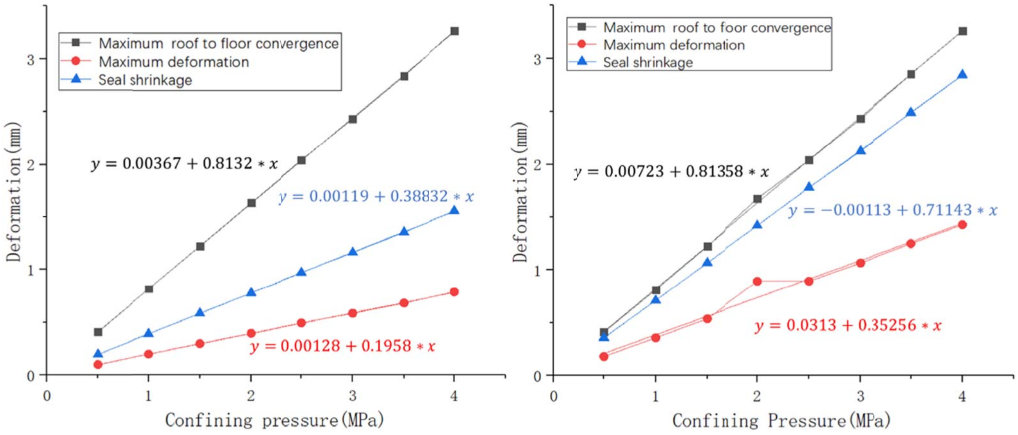


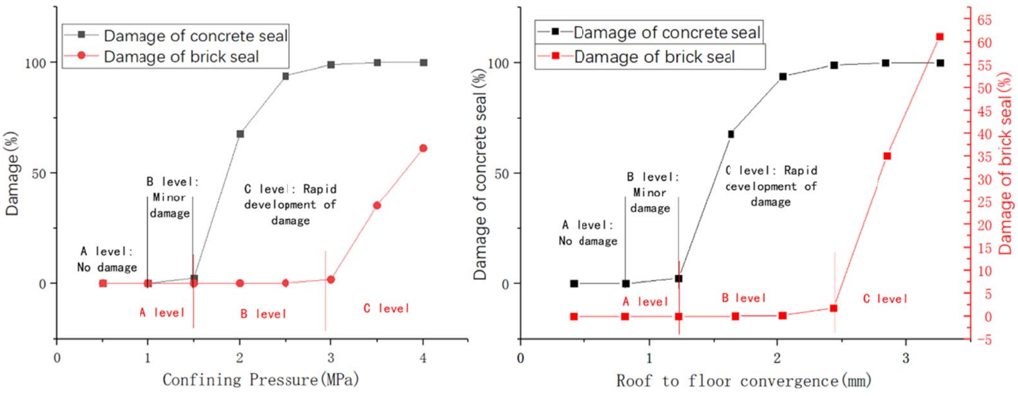
Fig. 10. Relationship between roof-to-floor moving convergence and ground pressure

floor moving convergence on the damage of the seal, the damage of the concrete seal and brick seal was explores with the roof-to-floor moving convergence being 1 mm, 2 mm, 3 mm and 4 mm at a ground pressure of 1 MPa, 2 MPa, 3 MPa, 4 MPa. As shown in Figure 11, whether the ground pressure or roof-to-floor moving convergence is used as the reference value, the damage of the seal can be divided into 3 levels. For the concrete seal, it can be divided into the following 3 levels.

A level (no damage): At a ground pressure of 0~1 MPa, the roof-to-floor moving convergence ranges from 0 to 0.82 mm, and there is no damage to the seal.

B level (minor damage): At a ground pressure of 1~1.5 MPa, the roof-to-floor moving convergence ranges from 0.82 to 1.2 mm, there is minor damage to the seal, and the damage grows slowly.

C level (rapid development of damage): When the ground pressure is greater than 2 MPa, the roof-to-floor moving convergence is greater than 1.2 mm, and the damage develops rapidly.



(a) Variation with ground pressure (b) Variation with roof-to-floor moving convergence

Fig. 11. Variation of seal damage

The damage to the brick seal can also be divided into the following 3 levels.

A level (no damage): At a ground pressure of 0~1.5 MPa, the roof-to-floor moving convergence ranges from 0 to 1.2 mm, and there is no damage to the seal.

B level (minor damage): At a ground pressure of 1.5~3 MPa, the roof-to-floor moving convergence ranges from 1.2 to 2.4 mm, there is minor damage to the seal, and the damage grows slowly.

C level (rapid development of damage): When the ground pressure is greater than 3 MPa, the roof-to-floor moving convergence is greater than 2.4 mm, and the damage develops rapidly.

The concrete seal is damaged at a ground pressure of 1 MPa and the brick seal is damaged at a ground pressure of 1.5 MPa. When the roof-to-floor moving convergence reaches 0.82 mm, the concrete seal is damaged, while the brick seal is damaged as the roof-to-floor moving convergence reaches 1.2 mm. This indicates that the brick seal outperforms the concrete seal in terms of the resistance to ground pressure, which is caused by the higher support strength of the concrete seal. In terms of nature, the brick seal plays a role of yielding pressure support, and the mine pressure is mostly borne by the surrounding rock; the #C40 concrete seal plays a role of pressure-bearing support, bearing more pressure than the brick seal. It thus clearly show that the high strength may not be a better option. Therefore, when there is a roof pressure, the protective effect by the brick seal may be better than the #C40 concrete seal.

5. Conclusions

The impact resistance and compressive capacity of seals constructed by different materials were explored in this study, and the following conclusions were drawn:

(1) First of all, the influence of slotting on the stability of seal under the explosion load was studied. For one thing, part of the impact on the seal was transferred to the surrounding rock to strengthen the bond between the seal and the surrounding rock. For another, the stress concentration of the rock was transferred to avoid damage failure caused by abundant stress concentration on the contact surface of the seal and rock. Secondly, the relationship between the performance of the seal and the slotting depth was explored. The relative displacement between the surrounding rock and the seal decreases with the increase of the slotting depth, and it tends to be stable as the slot depth reaches 20 cm. Meanwhile, as the slot depth increases, the maximum tensile stress of the seal and the surrounding rock increases sharply first and then decreases. When the slotting depth increases to 20 cm, the tensile stress is transformed from the high stress zone to the stable stress zone, with the optimal slotting depth being 20 cm.

(2) The influence of ground pressure (roof-to-floor moving convergence) on the protective function of the seal was studied, and the damage under the ground pressure was divided into 3 levels, i.e. no damage, minor damage stage and rapid development of damage. At the level of no damage, the ground pressure forms a prestressed structure to enhance the protective effect of the seal; at the level of minor damage, the seal is slightly damaged, and the damage grows at a slow rate; at the level of rapid development of damage, the seal suffers from extensive damage and the damage is rapidly growing.

(3) The relationship between the ground pressure and roof-to-floor moving convergence was studied. Due to the supporting effect of the seal on the roadway, there is a certain deviation between the ground pressure and roof-to-floor moving convergence. However,

under the same ground pressure, the concrete seal and the brick seal have basically the same roof-to-floor moving convergence, verifying the feasibility of replacing the ground pressure with roof-to-floor moving convergence to analyze relevant performance of the seal.

(4) The impact resistance and compressive capacity of the brick seal and the #C40 concrete seal were comprehensively compared. Under the explosion load, the concrete seal obviously outperforms the brick seal in terms of impact resistance, and it is more suitable for slotting. Nonetheless, when the ground pressure is obvious, the brick seal has a stronger compressive capacity than the concrete seal featuring pressure-bearing support, because the brick seal is less likely to be damaged due to its yielding pressure support. Therefore, a variety of factors on the site should be considered while choosing the materials to construct the seal.

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