Mechanism of Rockburst Prevention in Deep Thick Coal Seams with Cemented Paste Backfill: A Case Study

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The aim of this study is to explore a safe mining method to effectively excavate the deep thick coal seams in rockburst-prone mines. Based on the theory of elastic foundation and geological conditions of the Xinhe Coal Mine, the cemented paste backfill (CPB) is proposed to prevent rockburst. In this study, the roof fracture mechanism of block caving mining (BCM) and CPB methods are established. Then, the stress evolution of the surrounding rock and the subsidence of roof strata with these two methods are compared. The results show that the maximum bending moment appears in the middle of the roof, and the value is far below the critical bending moment of the roof by using the CPB. While using the BCM, this value exceeds the critical bending moment of the roof, which may trigger rockburst-related problems. In addition, there is no first weighting and periodic weighting phenomena by using the CPB method as the overburden pressure is gradually transferred to the backfill body, resulting in a safer mining condition. Furthermore, the engineering application indicates that the frequency of daily microseismic events and the burst energy are significantly reduced by using the CPB.

1. Introduction

In China, coal has been the primary source of energy for decades [1, 2]. As shallow resources are gradually depleted, the exploitation of coal resource extends from the shallow into the deep, where the high in situ stress is a serious threat to the safety of the mine production [3]. Specifically, the in situ stress increases significantly, and it changes from static stress to dynamic stress status. In some cases, the horizontal in situ stress may exceed the vertical in situ stress [4]. The high stress results in fracture initiation, and the propagation of the fracture increases the risk of mine safety [5–7]. The surrounding rock deformation of the roadway and stope increases with the excavation depth, as well as the frequency and energy of rockburst. This poses the potential of instantaneously releasing a large amount of energy, which is easy to cause rockburst and other disasters.

The mechanism of the rockburst has attracted lots of research interests in the literature. Among these mechanisms of the rockburst, the strength theory, energy theory, shock tendency theory, and the “three criteria” theory are widely acknowledged [8–10]. Pan et al. [11–13] summarised three types of rockburst based on the characteristics of multiple mines with rockburst disasters in China, namely, coal compression type, roof fracture type, and fault-dislocation type. They proposed relevant prevention and control methods accordingly. Qi et al. [14–17] did extensive research on factors that affect rockburst. They found that the source of the stress was a controllable factor in preventing rockburst. They put forward a stress control theory for rockburst-prone mines. Dong et al. [18, 19] derived energy concentration expressions for underground mining, and they found that the stored strain energy increased quadratically with time.
However, these studies mainly focused on the passive control after the formation of concentrated stress. In this study, we propose the cemented paste backfill (CPB), an active control method for rockburst-prone mines. The CPB has been used in many fields, which has great potential in maintaining stability of surrounding rock [20–22]. Numerous analytical solutions and numerical simulations have been carried out on CPB regarding its characteristics and usage in underground mines [23–26]. The backfill body can effectively avoid the formation of the concentrated stress during mining operations, thereby actively preventing and controlling rockburst events. This technology is successfully applied to Xinhe Coal Mine, which is located in the west of Jining City and around 7.5 km east of Jiaxiang County. The average buried depth of the mining area, #730, is 1137 m. There are dense villages on the surface of the mining area, and railways and highways cross the mining area. The coal thickness is 8.7–10.7 m with an average thickness of 9.9 m. The CPB #730 mining area studied in this paper is in the southeast of the mine, with the strike length of 1469 to 2009 m, and dip length of 318 to 1518 m. The surface within the mining area is mainly dominated by farmland, and the main areas of influence are six villages, such as Nanliu Village, Dongli Village, and Changma Village. The location and boundary of the mine is shown in Figure 1. Based on the geological condition, the mined coal seam is categorised as type III, which is a rockburst-prone coal seam.

2. Mechanism of CPB for Rockburst Prevention

2.1. Mechanism of Rockburst. Assuming that the strata is under elastic condition in this calculation. The overburden pressure is simplified as an evenly distributed compression pressure. For simplicity, the dip angle of the coal seam is considered as zero, which means the coal seam is flat. Figure 2 demonstrates the simplified analytical model of roof fracture during mining excavation. Due to the hard roof strata of the coal seam, the surrounding rock is stable at the initial stage of mining. As the working face advances, the tensile stress increases, and the tension area continues to expand. Under this condition, the rock gradually becomes a strain-softening material. The surrounding rock is composed of a stable roof elastic area $W_{xz}$, a stable coal seam elastic area $W_{sz}$, an unstable roof softening area $W_{xc}$, and an unstable coal seam softening area $W_{sc}$. When the distance of the suspended goaf increases to a certain value, the unstable roof $W_{xc}$ area rapidly expands along the tensile softening zone. Then, the roof strata break, causing the sudden release of the accumulated strain energy in the roof $W_{xz}$. This results in a rockburst.
2.2. Roof Deformation with Block Caving Mining (BCM) Method. According to the theory of elastic foundation [27–29], the rockburst analysis model is established (see Figure 3). Assuming that the elastic foundation coefficient of coal is \( k_l \), the total length of the goaf is \( 2L \), the thickness of the roof is \( H \), and the elastic modulus is \( E \). The stress of overlying strata is \( P \), which is evenly distributed on the upper surface of the roof.

As the model is symmetric, the half of the model is used for analysis. The deflection of the roof is expressed as

\[
EI \frac{d^4 \omega(x)}{dx^4} = \begin{cases} P, & 0 \leq x \leq L, \\ -k_l \omega(x) + P, & x \geq L. \end{cases}
\]

(1)

The general solution of the nonhomogeneous differential Equation (1) is

\[
\omega(x) = \begin{cases} \frac{1}{EI} \left( \frac{P x^4}{24} + \frac{c_1 x^3}{6} + \frac{c_2 x^2}{2} + c_3 x + c_4 \right), & 0 \leq x \leq L, \\ e^{a x} [c_5 \sin (ax) + c_6 \cos (ax)] + e^{-a x} [c_7 \sin (ax) + c_8 \cos (ax)] + \frac{P}{k_l}, & x \geq L, \end{cases}
\]

(2)

where \( a = \sqrt{k_l/4EI} \) and \( c_1, \ldots, c_8 \) are the integral constants and \( k_l \) is the foundation coefficient of coal.

The boundary conditions of Equation (2) are:

\[
x = 0, \quad \frac{d \omega(x)}{dx} = 0, \quad \frac{d^3 \omega(x)}{dx^3} = 0.
\]

(3)

\( x = L \); the functions \( \omega(x), d\omega(x)/dx, \) and \( d^3 \omega(x)/dx^3 \) are continuous.

\( x \rightarrow \infty, \) \( d\omega(x)/dx = 0, \) and \( \omega(x) \) is a finite value.

Therefore, the integral constants are resolved, and \( c_1 = c_3 = c_5 = c_6 = 0 \). Substituting the integral constants into Equation (2), the deflection equation of the roof is derived as

\[
\omega(x) = \begin{cases} \frac{1}{EI} \left( \frac{P x^4}{24} + \frac{c_2 x^2}{2} + c_4 \right), & 0 \leq x \leq L, \\ e^{-a x} [c_7 \sin (ax) + c_8 \cos (ax)] + \frac{P}{k_l}, & x \geq L. \end{cases}
\]

(4)

The bending moment of the roof is then calculated as

\[
M(x) = -EI \frac{d^2 \omega(x)}{dx^2} = -EI \left( \frac{P x^2}{24} + 2c_2 \right) + \frac{PL^2}{6} \left( \frac{a^2L^2 + 3aL + 3}{aL(aL + 1)} \right).
\]

(5)

From Equation (5), we can know that \( |M(0)| - |M(L)| = PL^2/2 \), and \( |M(0)| > |M(L)| \). The maximum value of the bending moment is \( M_{\text{max}}|_{x=0} \) and \( M_{\text{max}} = M(0) \). Therefore, the maximum tensile stress at the centre of the goaf is \( \sigma_{\text{max}} = 6M_{\text{max}}/H^2 \). Substituting \( \sigma_{\text{max}} \) into Equation (5), the critical stress condition for rockburst is expressed as

\[
\sigma_{\text{max}} = \sigma_i = \frac{6M_{\text{max}}|_{x=0}}{H^2} = \frac{PL^2}{H^2} \left( \frac{a^2L^2 + 3aL + 3}{aL(aL + 1)} \right).
\]

(6)

2.3. Roof Deformation with CPB. Figure 4 shows the simplified analytical model with the CPB. The roof control area of the hydraulic support is simplified as a rigid elastic foundation with a length of \( L \). The elastic foundation coefficient of the hydraulic support is \( k_s \), the elastic foundation coefficient of coal is \( k_l \), and the elastic foundation coefficient of the backfill body is \( k_s \).

Based on the theory of elastic foundation, the deflection of the roof in Figure 4 is expressed as

\[
EI \frac{d^4 \omega(x)}{dx^4} = \begin{cases} -k_s \omega(x) + P, & x < 0, \\ -k_s \omega(x) + P, & 0 \leq x \leq L, \\ -k_s \omega(x) + P, & x > L. \end{cases}
\]

(7)
The general solution of Equation (7) is

\[
\omega(x) = \begin{cases} 
  e^{\alpha x} \left[ c_1 \sin(\alpha x) + c_2 \cos(\alpha x) \right] + P \frac{K_i}{k_i}, & x < 0, \\
  e^{\beta x} \left[ c_5 \sin(\beta x) + c_6 \cos(\beta x) \right] + P \frac{K_\omega}{k_\omega}, & 0 < x < L, \\
  e^{\gamma x} \left[ c_9 \sin(\gamma x) + c_{10} \cos(\gamma x) \right] + P \frac{K_{\omega}}{k_{\omega}}, & x \geq L,
\end{cases}
\]

where \( \alpha = \sqrt{k_i/4EI} \) and \( c_1, \ldots, c_{12} \) are integral constants.

Knowing that the continuity conditions between sections of the roof at locations of 0 and L are expressed as: \( \omega_1(0) = \omega_2(0), \theta_1(0) = \theta_2(0), M_1(0) = M_2(0), \) and \( Q_1(0) = Q_2(0) \) and \( \omega_1(L) = \omega_2(L), \theta_1(L) = \theta_2(L), M_1(L) = M_2(L), \) and \( Q_1(L) = Q_2(L) \), respectively. When \( x > 0, x \to \infty, d\omega(x)/dx = 0, \omega(x) \) is a finite value. While when \( x < 0, x \to \infty, d\omega(x)/dx = 0, \omega(x) \) is an infinite value; therefore, \( c_5 = c_4 = c_9 = c_{10} = 0 \). Knowing that there is a certain filling distance from the working face, the deflection and bending moment are the largest at the coal wall. Therefore, the rockburst in the CPB will only occur in the roof control area and the coal wall. So, considering the boundary conditions and the derivative continuity conditions, we have \( c_1 = -(P\beta^2(\alpha - \beta))/(k_z(\alpha^2 + \alpha^2\beta + \alpha^2\beta^2)), c_2 = P\beta^2/(k_z(\alpha^2 + \beta^2)), c_3 = (P\alpha^2(\alpha - \beta))/(k_z(\alpha^2 + \alpha^2\beta + \alpha^2\beta^2)), \) and \( c_4 = -(P\alpha^2/(k_z(\alpha^2 + \beta^2))) \). Substituting the boundary conditions and constants into Equation (8), the deflection equation of the roof is

\[
\omega(x) = \begin{cases} 
  e^{\alpha x} \frac{P\beta^2(\alpha - \beta)}{k_z(\alpha^2 + \alpha^2\beta + \alpha^2\beta^2)} \sin(\alpha x) + \frac{P\beta^2}{k_z(\alpha^2 + \beta^2)} \cos(\alpha x), & x \leq 0, \\
  e^{-\beta x} \frac{P\alpha^2(\alpha - \beta)}{k_z(\alpha^2 + \alpha^2\beta + \alpha^2\beta^2)} \sin(\beta x) - \frac{P\alpha^2}{k_z(\alpha^2 + \beta^2)} \cos(\beta x) + \frac{P}{k_z}, & 0 < x < L.
\end{cases}
\]

It can be seen from Equation (9) that the bending moment equation of the roof is

\[
M(x) = -ET \frac{d^2\omega}{dx^2} = -ET \begin{bmatrix} 
  e^{-\beta x} \beta^2 \left( \frac{P\alpha^2(\alpha - \beta) \sin(\beta x)}{k_z(\alpha^2 + \alpha^2\beta + \alpha^2\beta^2)} - \frac{P\alpha^2 \cos(\beta x)}{k_z(\alpha^2 + \beta^2)} \right) \\
  -2e^{-\beta x} \beta \left( \frac{P\alpha^2(\alpha - \beta) \beta \cos(\beta x)}{k_z(\alpha^2 + \alpha^2\beta + \alpha^2\beta^2)} + \frac{P\alpha^2 \beta \sin(\beta x)}{k_z(\alpha^2 + \beta^2)} \right) \\
  +e^{-\beta x} \left( \frac{P\alpha^2(\alpha - \beta)\beta^2 \sin(\beta x)}{k_z(\alpha^2 + \alpha^2\beta + \alpha^2\beta^2)} + \frac{P\alpha^2 \beta^2 \cos(\beta x)}{k_z(\alpha^2 + \beta^2)} \right)
\end{bmatrix}.
\]
Analysing Equation (10), we can get $M_{\text{max}}|_{x=0}$ and $M_{\text{max}} = M(0)$. Substituting them into Equation (10), then the maximum tensile stress of the roof is

$$\sigma_{\text{max}} = \sigma_i = \frac{6M_{\text{max}}}{H^2} = \frac{12Et\alpha^2 P \beta^2 (\alpha - \beta)}{H^2 \cdot K_2 (\alpha^3 + \alpha^2 \beta + \alpha \beta^2 + \beta^3)}.$$  \hspace{1cm} (11)

2.4. Mechanism of Rockburst Prevention with CPB. According to the geological conditions of the Xinhe Coal Mine, the average buried depth of the coal seam is 1137 m. So, the overburden pressure $P$ is simplified as 25 MPa. The elastic modulus of the coal and rock stratum are 3.5 GPa and 18 GPa, respectively. The moment of inertia is $I = bH^3/12$, where $b = 1$ and $H = 12.6$ m. The coefficient of the elastic foundation of the coal $k_i$ is $2 \times 10^8$, and the elastic foundation of the backfill body $k_z$ is 4 $\times$ 10$^7$. In addition, the elastic foundation coefficient of the hydraulic support $k_z$ is 1.8 $\times$ 10$^7$. In the BCM method, the length of the unsupported area in the goaf $L$ is 120 m, while in the CBM method, this value reduces to $L = 10$ m. The length of the coal pillar is 50 m.

Based on the first strength theory, when the maximum tensile stress exceeds the tensile strength, then the material breaks. In this calculation, the tensile strength of the roof stratum is $|\sigma| = 28.4$ MPa. Therefore, the critical bending moment for the roof breaking is calculated as $7.5 \times 10^8$ N.m.

Figure 5 compares the roof subsidence by using BCM and CPB methods. The calculated mining height of the first slice is 3.3 m with the length of the working face of 120 m. By using the BCM method, it can be seen that the roof gradually subsides to the maximum value of 3.3 m at the middle of the goaf area. The subsidence decreases to both ends (see in Figure 5(a)). Figure 5(b) shows the roof subsidence curve with the CPB method. The roof subsides to a stable value of 2.7 m after advancing 50 m from the working face.

Figure 6(a) shows that when mining with the BCM method, both positive and negative bending moments appear in the goaf area. In the middle of the roof, the bending moment is positive with a maximum value of $1.5 \times 10^9$ N.m. In the CPB method, the roof subsides to a stable value of 2.7 m after advancing 50 m from the working face.
In 40 m away from the centre of the goaf area, the negative bending moment appears on both sides with the maximum value of $3 \times 10^{10}$ N.m. Under the positive bending moment, the tensile stress appears in the lower part of the roof, while under the negative bending moment, the tensile stress reaches its maximum in the upper part of the roof. Based on the geological condition, the tensile strength of the roof is $7.5 \times 10^8$ N.m. Therefore, under the BCM method, the roof is unstable, and the mining-induced accumulated energy would be suddenly released, resulting in rockburst problems. However, by using the CPB method, the maximum bending moment of the roof is only $4.2 \times 10^8$ N.m (see in Figure 6(b)). The lower part of the roof stratum is under tension status. The roof is stable as the bending moment is lower than the critical value of $7.5 \times 10^8$ N.m. It is noticed that in the coal body supported area, the maximum bending moment exceeds the critical value; however, the tension area appears in the upper part of the roof stratum, which is compressed by the overlying strata. As a result, the roof will remain stable under such conditions.

### 3. Numerical Simulation

#### 3.1. Numerical Model

This numerical simulation is conducted based on the Xinhe Coal Mine condition. The mined #3 coal seam is buried 940 to 1335 m, with the average thickness of 9.9 m. The coal seam is mined out in three slices with the height of each slice of 3.3 m. The purpose of this model is to predict the stress and roof subsidence evolution of the surrounding rock during the mining retreat. The dimensions of the model are $300 \times 100 \times 50$ m (length $\times$ height $\times$ width). The bottom of the model is fixed, and the four vertical planes are restricted from motion in the normal directions, while the upper surface is totally free to move [4]. To minimise the effect of the boundary conditions, a 40 m boundary away from the edge of the model is reserved. A uniform distributed load of 25 MPa is applied on the top of the model to mimic the weight of overburden strata. The roof of the #3 coal seam is mainly dominated by the mud rock and the powder sandstone with the thickness of 0.63 to 13.96 m. The strength of the roof ranges from 3.2 to 72.1 MPa. The floor of the #3 coal seam mainly consists of the mud rock with the thickness of 0.6 to 12.1 m. The strength of the floor ranges from 1.3 to 66.6 MPa. In addition, the geotechnical report indicates that the roof of the #3 coal seam is more stable than the floor of the seam. Table 1 summarises the physical and mechanical parameters of each rock stratum of the model. The numerical calculation model diagram is shown in Figure 7.

#### 3.2. Deformation of the Surrounding Rock

Figure 8(a) shows the roof subsidence curve with the CPB method. When the third slice is mined, the initial value of the roof subsidence is 0.66 m, which is the stable subsidence value of the second layer. It is noticed that there is no increment of roof subsidence until the CPB working face advances to 25 m. The roof subsidence gradually reaches 0.63 m when the CPB working face advances to 70 m. So, the final subsidence of the roof after the whole thickness of the coal seam is mined is 1.29 m by using the CPB method. The subsidence coefficient is calculated as 0.13. While by using the BCM method (see in Figure 8(b)), the final subsidence reaches 9.9 m after the working face advances to 105 m. There is a sharp increase of the subsidence when the working face advances to 70 m. The subsidence increases from 1 m at the advancing distance of 35 m to 3.5 m at

| Stratum          | Thickness (m) | Density (kg/m$^3$) | Tensile strength (MPa) | Friction angle ($) | Cohesion (MPa) | Bulk modulus (GPa) | Shear modulus (GPa) |
|------------------|---------------|--------------------|------------------------|-------------------|----------------|-------------------|---------------------|
| Basic roof       | 6.5           | 2600               | 40                     | 42                | 1.6            | 8.4               | 3                   |
| Immediate roof   | 2             | 2400               | 5.6                    | 30                | 1.5            | 1.9               | 0.9                 |
| #3 coal          | 9.9           | 1380               | 1.9                    | 28                | 0.12           | 0.9               | 0.09                |
| Immediate floor  | 1.5           | 2400               | 6                      | 35                | 1.2            | 1.9               | 0.8                 |
| Basic floor      | 6             | 2600               | 35                     | 45                | 1.6            | 8.8               | 6.2                 |

Figure 7: Numerical model simulation.
the advancing distance of 70 m. This is because the basic roof is broken after reaching its strength as there is no additional support in the goaf area.

3.3. Stress Evolution. By using the CPB method, the stress concentration occurs in the roof behind the working face, and the peak stress concentration gradually increases as the working face advances (see in Figure 9(a)). The peak stress reaches 55 MPa when the working face advances to 220 m. In the roof stratum behind the working face, the concentration stress is released due to the backfill body, where the stress decreasing zone is formed. The maximum compression stress appears near the coal pillar of the working face and then decreases to in situ stress. As the working face advances, the stress is gradually transferred to the coal pillars in front of the working face, and the peak stress reaches 60 MPa. Figure 9(b) shows the vertical stress distribution
with the BCM method. With the advancement of the working face, the stress is gradually released, forming a stress reduction zone. However, the stress concentrates in the coal pillar on both sides of the working face. The concentrated stress behind the working face is higher than that ahead of the working face. As the working face advances, the maximum vertical stress of the roof near the coal pillar is 75 MPa, while the stress of the roof in front of the working face does not change much with the maximum stress of 65 MPa.

Figure 10 shows the horizontal stress of the roof after the whole seam has been excavated by using CPB and BCM methods. It can be seen that the peak value of the horizontal stress is 65 MPa with the CPB method, and the peak value appears at 5.8 m away from the coal pillar. While using the BCM method, the peak value of the horizontal stress is 25 MPa, and the peak value appears at 14.2 m from the coal pillar. It is noticed that the increment of the horizontal stress increases the strength of the bearing capacity. Therefore, the bearing capacity of the boundary coal pillar in the CPB method is greater than that in the BCM method.

Through the comparison above between the CPB and BCM, we can see that the proposed CPB method can significantly reduce the potential hazards of rockburst in rockburst-prone mines. The stress status by using CPB has greatly improved and the concentrated stress in the coal body is less than that of using BCM. In addition, the subsidence of roof stratum is less with CPB method. This study investigates the mechanism of the CPB method in preventing rockburst. The current solution only focuses on the elastic assumption and simplifies several conditions in the calculation. However, the results indicate that the proposed method is an efficient way to reduce the rockburst hazards. In our future study, more complex conditions including elasto-plastic rock material conditions will be considered.

4. Engineering Application

In the field application, engineers usually use microseismic technology to monitor the rockburst. Before and after the rockburst, the frequency and energy of coal mine microseismic events will change significantly. When the frequency of microseismic events gradually decreases, the rockburst will not occur. Because the released energy is very small under this situation. The microseismic frequency and energy of the #730 mining area were monitored between September 2019 and December 2019 with a total of 91 days (see in Figure 11).

It shows that under the BCM method, the maximum daily microseismic frequency reached 87 on October 28, with the maximum burst energy of 141810 J. The average daily microseismic frequency reached 40 (see in Figure 11(a)). Figure 11(b) shows that the maximum daily microseismic frequency under CPB was 12 with the maximum impact energy of 18810 J. The average daily microseismic frequency reached 3. Compared to the BCM method, the CPB greatly reduced the frequency of daily microseismic events and burst energy. During filling mining, the frequency of microseismic events was relatively low and showed an obvious downward trend. In addition, the released energy was also relatively small by using the CPB. It shows that the risk of rockburst caused by CPB was low. Therefore, by using the CPB, the risk of having a rockburst is under control.

5. Conclusion

The rockburst is a serious hazard in deep mining and has a great influence on the safety and mine production. This paper proposed the cement paste backfill method to prevent rockburst. Based on the theory of elastic foundation, the mechanical calculation model was established. Numerical models were established to reveal the mechanism of CPB method in controlling rockburst. In addition, the field application indicated that the proposed solution was successful in the rockburst-prone mine. The conclusions were summarised as follows:

(1) The bending moment of the roof by using CPB was significantly reduced. The CPB method reduced the span and the bending moment of the roof. The maximum positive bending moment was calculated as $4.2 \times 10^8$ N·m, which was below the limit bending moment of the roof. This reduced the probability
of the sudden failure of the roof, thereby reducing the probability of the rockburst problem

(2) The sudden release of the accumulated energy may cause rockburst disasters. However, the first weighting and periodic weighting will not happen by using the CPB method. The overburden pressure is gradually transferred to the backfill body, so there will be no accumulation and sudden release of energy

(3) Compared with the BCM method, the frequency of microseismic events during the CPB is relatively low. The energy released is also relatively small. Therefore, the risk of rockburst caused by the CPB method is low

Data Availability

Data are available on request. Please contact Professor Qingliang Chang for data if needed (zkdcql@163.com).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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