Research Article

Research on Goaf Retaining Technology of Double-Layer “Combined” Filling Body in High Gas Mine

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Abstract In high gas mines, the safety accidents of coal seam spontaneous combustion and gas leakage in goaf caused by fresh air flow entering goaf due to loose roof connection of filling body beside goaf are easy to occur. In order to solve such problems, this paper proposes the gob-retaining technology of the “combined” filling body at the side of the roadway. The upper layer of the “combined” filling body is constructed with high-water material as the “connecting top layer” so that the deformation form of the filling body is consistent with the broken characteristics of the roof, and the lower layer is constructed with concrete as the “supporting layer” to achieve sufficient support strength. The “combined” filling body can not only ensure the stability of roadway surrounding rock but also a timely closed goaf. The gob-retaining technology of the “combined” filling body was applied in the field of coal mine 2603 working face. Based on the engineering background, the mechanical model was established to calculate cutting resistance of the filling body, and Flac3D software was utilized to optimum parameters of the “combined” filling body. According to the field monitoring results, the “combined” filling wall at the side of the roadway effectively controls the stability of surrounding rock and the gas concentration in the roadway.

1. Introduction

The core of goaf retention technology is to make the basic roof above the goaf collapse along the filling body beside the goaf in time, avoiding the formation of cantilever beam structure [1–3]. In existing studies, the timely caving technology of the basic roof has been basically matured. However, in high-gas mines, the traditional roadway side filling body cannot guarantee sufficient strength to maintain the stability of the roadway and appropriate expansion to seal the goaf under pressure [4–7]. Therefore, how to realize the basic roof caving and at the same time to quickly close the goaf-retaining technology has yet to be studied.

Many scholars have carried out a large number of studies on the filling method of filling body beside goaf retaining roadway. Bai Jianbiao proposed the construction method of high-water material [8–11]. He et al. proposed the filling method of coal gangue paste material [12]. Zhang proposed the closed die casting masonry filling method [13]. Ma et al. proposed the filling method of fly ash-based cemented material [14]. Chen et al. established a mechanical model of reinforcing the filling body beside the roadway with reinforcement net and pulling anchor bolt in view of the insufficient strength of the filling body beside the roadway with high-water material, and studied and analyzed the reinforcement mechanism of reinforcing the filling body with reinforcement net and pulling anchor bolt in different deformation states [15]. Meng proposed the surrounding rock control technology, which was composed of the active support technology of high-prestressed bolt cable in roadway and the passive support technology of early-strength and collapsible roadway side filling body [16].

According to previous studies, the filling body beside the roadway should not only have sufficient support strength but
also have a certain amount of shrinkage [17–20] so as to achieve the purpose of maintaining roadway stability and closed goaf. Based on the engineering technology background of 2603 working face of Zhangcun Coal Mine, Lu’an Group, this paper puts forward the gob-side retaining technology of filling body suitable for high gaseous mine.

2. Engineering Geological Conditions

2.1. Occurrence Conditions and Lithologic Characteristics of Coal Seams. The 2603 working face of Zhangcun Coal Mine is located in no. 3 coal seam, with an average thickness of 4.93 m and an average dip angle of 4°. The coal seam structure is relatively simple. The average thickness of immediate roof is 3.65 m. The average thickness of the basic roof is 12.4 m. The average thickness of direct bottom is 5.7 m. The average thickness of the base is 1.85 m. According to the gas geological map and measured gas content, the total gas content is 8.2 m³/t–11.2 m³/t. The lithologic histogram of roof and floor is shown in Figure 1, and the mechanical parameters of coal and rock in roadway are shown in Table 1.

2.2. Roadway Layout. 3# coal seam is the last main mining seam of Zhangcun Mine. In the tunneling process, with the continuous increase of mining depth, the gas content of #3 coal seam shows an increasing trend. To relieve the tension of mining and replace and solve the problems of gas concentration exceeding limit in the working face, the “combination” filling wall is adopted to keep the roadway in the 2603 working face. The roadway layout of 2603 working face is shown in Figure 2.

![Figure 1: Lithologic histogram of roof and floor of coal seam.](image)

Table 1: Mechanical parameters of coal and rock in transport and roadway.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>$H_0$ $(m)$</th>
<th>$\sigma_i$ (MPa)</th>
<th>$\sigma_t$ (MPa)</th>
<th>$\sigma_{j}$ (MPa)</th>
<th>$\lambda$</th>
<th>$E$ (GPa)</th>
<th>$\phi$ (°)</th>
<th>$\rho$ $(kg/m^3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poststone</td>
<td>7.83</td>
<td>55.4</td>
<td>5.3</td>
<td>12.6</td>
<td>0.25</td>
<td>45.0</td>
<td>45</td>
<td>2600</td>
</tr>
<tr>
<td>Mudstone</td>
<td>2.49</td>
<td>28.0</td>
<td>1.7</td>
<td>5.6</td>
<td>0.28</td>
<td>11.6</td>
<td>25</td>
<td>2500</td>
</tr>
<tr>
<td>3# coal</td>
<td>6.53</td>
<td>21.0</td>
<td>2.0</td>
<td>1.4</td>
<td>0.13</td>
<td>14.7</td>
<td>17</td>
<td>1250</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>2.83</td>
<td>28.0</td>
<td>2.7</td>
<td>7.0</td>
<td>0.28</td>
<td>15.5</td>
<td>23</td>
<td>2500</td>
</tr>
<tr>
<td>Poststone</td>
<td>5.04</td>
<td>62.4</td>
<td>5.6</td>
<td>14.0</td>
<td>0.25</td>
<td>48.0</td>
<td>40</td>
<td>2700</td>
</tr>
</tbody>
</table>

The mechanical model of interaction between roadway filling body and roof is shown in Figure 3. The section is made at the position of the middle broken line of the slab.

Where $q$ is the weight per unit length of AC block, kg/m; $q_0$ is the unit length weight of direct roof, kg/m; $M_0$ is the residual bending moment of A terminal, N·m; $X_0$ is the distance between basic roof breaking line and coal wall, m; $X_0$ is the side abutment pressure per unit length, N/m; $N_0$ is the side coal side supporting force, N; $N_c$ is the side shear stress of roof goaf, MPa; $a$ is the width of lane retention, m; $d$ is the width of roadway side filling body, m; $P_a$ is the support resistance of roadway side filling body, MN/m; $e$ is the span of basic roof breakage in goaf, m; $M_b$ is the ultimate bending moment of the basic roof rock N·m; $T_p$ is the thrust of the basic roof on both sides along the break line, MPa.

The above model is simplified as follows:

1. For bearing the pressure of the basic roof strata, the support resistance generated by the active support technology of bolt and cable in the roadway is far less than that of the filling body beside the roadway. Therefore, the influence of the support resistance in the roadway is ignored when the mechanical model of goaf retaining is established.

2. The shear force between layers of overlying strata in goaf retaining roadway is zero, and there is no interlayer slip phenomenon.

3. The weight of the overlying strata of the basic roof is regarded as evenly distributed on the basic roof strata.
Bending subsidence and fracture subsidence occur on the goaf side of the basic roof with the side edge line of goaf of the filling body beside the roadway as the rotating axis.

Before the roof strata are cut off by the filling body beside the roadway, the supporting force of caving gangue ingoaf on the basic top block AC is zero, and the vertical shear stress on the goaf side is the horizontal thrust along the rock strata direction. The calculation formula is shown as follows:

\[ T_C = \frac{L_S \cdot q \cos \alpha}{2(m - \Delta S_C)} \]  

where \( \alpha \) is the coal seam dip angle, \(^\circ\); \( L_S-AC \) is the block length, namely, the limit span of basic roof fracture, \( m \); \( m \) is the basic roof thickness, \( m \); \( \Delta S_C \) is the amount of subsidence at the end of the C block when it is cut, \( m \).

The width of the filling wall can be calculated by establishing the mechanical equations of AB and BC rock blocks with the balance method.

BC block, perpendicular to inclination \( \alpha \),

\[ N_B - q \cos \theta - N_C = 0. \]  

Parallel to the direction, \( \sum F_x = 0 \), then theta:

\[ T_B = T_C + q \sin \alpha \cdot e, \]
\[ \sum M_B = 0, \]
\[ M_L - \frac{1}{2} q \cos \theta \cdot e^2 - N_C \cdot e + T_C (h - \Delta S_C) + q \sin \alpha \cdot e \left( \frac{h}{2} - \Delta S_C \right) = 0, \]

where \( \Delta S_C \) is the subsidence amount of C terminal before basic roof collapse.

AB block \( \sum M_A = 0 \), then theta:

\[ P_q \left( x_0 + c + \frac{d}{2} \right) + \int_0^{x_0} \sigma_y (x_0 - x)dx + M_0 + T_B (h - \Delta S_B) + q \sin \alpha (x_0 + c + d), \]
\[ \left( \frac{h}{2} - \Delta S_B \right) - \frac{1}{2} (q + q_0) \cos \alpha \cdot (x_0 + c + d)^2 - N_B (x_0 + c + d) - M_L = 0, \]

where \( \Delta S_B \) is the subsidence amount of terminal B before basic roof collapse.

The calculated top-cutting resistance is 19.86 MN/m. When the width of backfill is 1.5 m, the strength connecting the backfill to the top layer is no less than 14 MPa, which can meet this requirement.

3. Stability Analysis of Retaining Wall Rock under Different Parameters of “Combined” Filling Body

3.1. Influence of Different Strength of “Composite” Wall on Stability of Surrounding Rock. According to the geological conditions of the field survey, a numerical calculation model was established on the basis of FLAC3D in a length of 200 m, a width of 100 m, and a height of 100 m. The vertical direction was divided into seven layers according to the distribution state of rock strata. The bottom plate was 30 m away from the bottom boundary of the model. In the model, the upper material of the “combined” filling body near the roadway is high-water material to increase the compressive characteristics of the filling body, and the lower material is concrete material to ensure the overall strength of the filling body. In the model, the Mohr–Coulomb model is adopted for coal seam, rock stratum, and filling body near the roadway. Mechanical properties of coal strata are shown in Table 1. Mechanical properties of concrete materials and high-water materials are shown in Table 2.
As the support layer of the “combined” backfill, the concrete material plays a decisive factor in the strength of the backfill. As the top layer of the “combined” backfill, the high-water material bears the compressible deformation characteristics of the backfill. Therefore, to investigate the influence of backfill strength on surrounding rock stability, numerical simulation was carried out on the surrounding rock stability at different strengths of 20, 30, 40, and 50 MPa supporting layers of “combined” backfill near the roadway, and the displacement variation of surrounding rock at 10 m behind the working face at 100 m was analyzed. The displacement of surrounding rock of roadway under different strength conditions of “combined” wall support layer is shown in Figure 4.

### Table 2: Mechanical properties of concrete materials and high-water materials.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>(\sigma_c)/(MPa)</th>
<th>(\sigma_t)/(MPa)</th>
<th>(\sigma_S)/(MPa)</th>
<th>E/(GPa)</th>
<th>(\phi)/(^o)</th>
<th>(c)/(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poststone</td>
<td>39</td>
<td>4</td>
<td>6.8</td>
<td>32.5</td>
<td>55</td>
<td>12</td>
</tr>
<tr>
<td>Mudstone</td>
<td>15.8</td>
<td>1.7</td>
<td>2.2</td>
<td>11.6</td>
<td>25</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Figure 4:** Displacement cloud diagram of surrounding rock of roadway under different strength of “combined” wall support layer (unit: mm). (a) 20 MPa. (b) 30 MPa. (c) 40 MPa. (d) 50 MPa.

3.2. **Influence of “Combined” Wall on Stability of Surrounding Rock.** The stability of surrounding rock under the different widths of 1.2, 1.5, 1.8, and 2.1 m of the “combined” filling body at the side of the roadway was numerically simulated, and the displacement variation of surrounding rock at 10 m behind the working face at 100 m was analyzed. The displacement of surrounding rock of roadway under different widths of “combined” walls is shown in Figure 5.

3.3. **Influence of Different Layered Heights of “Composite” Wall on Stability of Surrounding Rock.** Numerical simulation was conducted on the stability of surrounding rock under the conditions of 300, 400, 500, and 600 mm heights of the top
layer of “combined” backfill body, respectively, and the displacement variation of surrounding rock at 10 m behind the working face at 100 m was analyzed. Figure 6 demonstrates the surrounding rock displacement that the upper layer is in various heights.

3.4. Analysis of Numerical Simulation Results. It is clearly observed that when the strength of the “composite” wall support layer is 40 MPa, the decreasing trend of top and bottom displacement slows down significantly. At this time, the top and bottom displacement is 188 mm, the two sides displacement is 28 mm, and the transverse deformation of the filling body is 3 mm. When the wall width is 1.5 m, the growth rate of roof and floor displacement slows down significantly and tends to be horizontal. Then, the roof and floor displacement is 101 mm, the two sides displacement is 22 mm, and the transverse deformation of filling body is −2 mm. When the top height of the “composite” wall is 400 mm, the displacement of the top, bottom, and two sides is the turning point, which is the minimum 252 mm, and the displacement of two sides is 41 mm. Then, the strength of the top after letting pressure is coupled with the strength of the roof rotation and subsidence process. From the three influencing factors of the strength of the support layer, the height of the top layer and the width of the filling body, the width of the filling body has the greatest influence on the “composite” wall. The displacement values of surrounding rock and filling body under three different influencing factors of “combination” support layer strength, wall width, and top layer height are shown in Figure 7.

4. Field Industrial Test

The maximum displacement of the top and bottom panels monitored on-site is 480 mm, and the maximum displacement of the two sides is 122 mm, both located at the end bracket. The average displacement of the top and bottom panels is 208 mm, and the average displacement of the two sides is 56 mm. The gas concentration reaches a maximum of 0.253% in the upper corner of the return air and then shows a downward trend until 0.132%. As can be seen from the effect of roadway retention and gas concentration, the “combined” filling wall has a significant effect on roadway...
Figure 6: Displacement cloud diagram of surrounding rock of roadway at different heights when the "combined" wall is connected to the top floor (unit: mm). (a) 300 mm. (b) 400 mm. (c) 500 mm. (d) 600 mm.

Figure 7: Displacement of surrounding rock and filling body under different influence factors of "composite wall." (a) Strengthen influence. (b) Width influence. (c) Height influence.
retention along goaf. The change value of roof and floor displacement in the top roadway monitored on-site is shown in Figure 8(a), and the change value of gas concentration is shown in Figure 8(b).

5. Conclusion

In this article, a novel gob-retaining technology of the “combined” filling body (GRT-CFB) at the side of the roadway was proposed. To verify the superiority of novel technology, a GTR-CFB was constructed at 2603 longwall panel in Zhangcun coal mines. Based on the mechanical model, FLAC3D was used to determine the optimum parameters of filling wall “combination.” The following conclusions are drawn:

(1) The traditional concrete filling wall and high-water material filling wall cannot achieve the goal of effective control of the surrounding rock and the airtight goaf; therefore, high gas coal mine is put forward in the “combination” on the wall filling way to pick the top above that can achieve rapid airtight mined-out area, below the support layer provides the main support for the wall, to ensure the stability of roadway surrounding rock and filling body.

(2) In the field practices, the lower 3300 mm of the “combined” filling wall is constructed with C40 concrete as the supporting layer, and the upper layer is constructed with 1.2 : 1 high-water material as the connecting top layer, making full use of the pressure-shrinkable characteristics of high-water material and the high-strength characteristics of concrete. Based on the field data, the newly proposed GRT-CFB can effectively support the upper stratum and isolate the waste gas in the gob.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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