Research Article

Study on Control Technology for Working Faces Passing through Long-Span Abandoned Roadways

Zhenghe Liu ¹, **Hailong Ye**¹, **Lusheng Yang**², **Shaohua Wang**¹, **Junwen Zhang** ³,
Baisheng Zhang⁴ and **Zhiqiang Li**⁵

¹Key Laboratory of In-Situ Property-Improving Mining of Ministry of Education, Taiyuan University of Technology, Taiyuan, Shanxi 030024, China

²Shanxi Institute of Energy, Yuci 030600, China

³School of Energy & Mining Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

⁴College of Mining Engineering, Taiyuan University of Technology, Taiyuan 030024, China

⁵Shanxi Jinneng Group Sanyuan Shikues Coal Industry Co., Ltd., Changzhi 047500, China

Correspondence should be addressed to Zhenghe Liu; liuzhenghe2001@163.com and Junwen Zhang; zhangjw@cumtb.edu.cn

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The width of an abandoned roadway has a great influence on the roof stability of the working face. According to the coal seam conditions of the 30106 working face in the Sanyuan Shiku mine, the advance of a working face through an abandoned roadway was studied by using theoretical analysis, similar material simulation, numerical simulation, and field testing to determine the law of stope roof fracture migration, the stress distribution characteristics, and the variation in support resistance. Several conclusions are drawn: (1) The roof of the overlying strata is fractured at the edge of the abandoned roadway in front of the coal pillar and rotates downward due to the run-through of the plastic zone between the working face and abandoned roadway. (2) The hydraulic support working resistance gradually increases with decreasing coal pillar width between the working face and abandoned roadway, and the working resistance of the support tends to peak when the plastic zone extends to the coal, resulting in 3~4 times the normal recovery. Leakage occurred in front of the support in the caving zone. (3) The analysis of the relationship between the support and surrounding rock with the mechanical model for calculating the support load allows the derivation of the support working resistance formula for a working face passing through an abandoned roadway. (4) When the working face is excavated to expose the abandoned roadway, the shrinkage of the front column of the hydraulic support is significantly greater than that of the back column, and the stability is greatly reduced. This problem can be effectively solved when the uniaxial compressive strength of the backfill ≥ 2 MPa. (5) The engineering practice showed that the danger of leakage and roof fracture impact load was eliminated with the mining pressure reduction after reinforcement measures were taken in the abandoned roadway. The working face passed the abandoned roadway safely, providing the theoretical basis and guidance for coal remining under similar conditions.

1. Introduction

The production system of the working face is composed of several coal seam roadways of different sizes, which are used for ventilation, transportation, walking, and equipment assembly. Before the 1990s, traditional pillar technologies such as knife pillars, roadway pillars, and residual pillars were widely used to mine thick coal seams, and the recovery rate was low. At the same time, there are many abandoned road-

ways due to the production changes and the layout of connecting roadways and production roadways in the residual coal recovery area [1, 2]. Under the long-term influence of roof pressure, gas, and water, the integrity of the residual coal and mine roof and floor becomes destroyed, the location and size of abandoned roadways become irregular, and the bearing capacity and stability of the coal worsens; thus, the response of strata pressure is an extremely complex rock mechanics problem related to rock cracking, fracture, and

seepage. The abandoned roadway is constantly exposed in the re-mining face; because the creep damage degree of the surrounding rock in the abandoned roadway is not clear and the broken structure and stress transfer law of the overlying rock during mining are not understood, numerous roof fall and pressure frame accidents, which cause serious damage to the workers' physical and mental health and production safety, occur [3, 4]. Therefore, it is of great significance to study the characteristics of overlying rock collapse and the law of stress evolution in goafs and to seek safe and low-cost control technology for re-mining faces.

In recent years, experts and scholars worldwide have performed research on rock failure and rock bridge coalescence related to mining engineering. In particular, many rock mechanics studies related to exposed abandoned roadways in working faces have been performed [5–13]. Zhang et al. [5] proposed that due to the existence of an abandoned roadway, the working face roof exhibited further developed fracture characteristics, while the supporting stress was noticeably concentrated at the pillar. Ma and Wang [6] used UDEC to establish a numerical model, which indicated that a bearing arch existed in the cataclastic regenerated roadway roof and that the arch rise underwent changes with an increase in the roof hanging time and with different support scenarios, and proposed an optimal roof support approach to control abandoned roadways. Kushwaha et al. [7] evaluated the safety of surface structures above old underground mine workings and proposed appropriate protective measures. Zhou et al. [8] analyzed the distribution law of gas on abandoned roadways and proposed surface-based radon detection to identify spontaneous combustion areas in the goafs of small coal mines. Fan et al. [9] researched the thermodynamic performance of the WS-CAES system and analyzed the suitability of roadways for compressed air storage, suggesting that the surrounding rock with a permeability of 10^{-16} to 10^{-19} m² could impose a significant effect on the leakage and storage efficiency.

Most of the related research objects have been abandoned roadways with a width of 2–4 m, and there is no research on long-span abandoned roadways (width 6–9 m), and the width of abandoned roadways, as a key parameter, has an important impact on stope stability. The previously proposed filling control measures are costly and have not been widely used at present. In this paper, the stope stability and control technology of exposed abandoned roadways in the working face are studied by means of physical simulation, theoretical analysis, and numerical simulation to provide a basis for taking corresponding prevention and control measures in the working face.

2. Similar Material Simulation

2.1. Geological Survey of the Working Face. The width of the 30106 working face is 124–160 m in the Sanyuan Shiku Coal Mine, the advancing length is approximately 600 m, the average thickness of the coal seam is 6.0 m, the roof is mudstone, fine sandstone, sandy mudstone, and siltstone, and the floor is siltstone. The average burial depth of the coal seam is 233.2 m. The geological conditions in the working face are

simple, and the working face will pass through the long-span roadway, as shown in Figure 1.

The on-site investigation indicates that the working face will pass through two abandoned roadways, numbered ① and ②, as shown in Figure 1. The number ① abandoned roadway has a large span, a width of 8 m, a height of 6 m, and an angle of 90° with the advancing direction of the working face, and the number ② abandoned roadway has a small span, 3 m wide, and 2.5 m high. The working face first passes through the number ① abandoned roadway. This time, the number ① abandoned roadway is taken as the research object to study the roof fracture characteristics of the long-span abandoned roadway, the stress distribution in the surrounding rock, and the working resistance of the support.

2.2. Similar Model Design. According to the occurrence condition of the coal seam and the principle of similarity simulation [14, 15], it is determined that the geometric similarity ratio C_L , bulk density similarity ratio C_γ , and stress similarity ratio C_σ of this test are $C_L = 1 : 40$, $C_\gamma = 1.7$, and $C_\sigma = C_\gamma C_L = 68$, respectively. The experiment adopts a plane strain flexible loading test device developed by the Institute of Mining Technology, Taiyuan University of Technology, with dimensions of 3 m × 3 m × 0.2 m (length × height × width), as shown in Figure 2. The thickness of the coal seam roof laid by the model is 72.2 m, the mass of the overlying strata with a thickness of 161 m is loaded in the form of a static load and uniform surface force, and the loading pressure is 0.08 MPa after considering the friction coefficient of the model. A pressure box is arranged in the rock strata; the stress data acquisition system is a TST3827 static stress-strain test analyzer, the displacement observation points are arranged in different layers of the roof strata, and the displacement change is measured with a Nikon DTM531E total station. The roof support of the working face uses a Changzhou HENG TUO Electronic weighing instrument Co., Ltd., weighing sensor connected with a strain gauge to test the working resistance, as shown in Figure 3.

According to the actual section size, the simulated abandoned roadway of coal seam excavation is 8 m × 6 m, the state of the goaf shown in Figure 2 is formed, and the working face cycle step of 15 mm is carried out, with six cycles a day.

In this simulation test, surrounding rock reinforcement measures are not taken in the abandoned roadway, and the characteristics of strata movement and deformation and the stress distribution law of the surrounding rock in the working face passing through a long-span abandoned roadway are studied.

2.3. Analysis of Similar Simulation Results

2.3.1. Characteristics of Strata Movement and Deformation. When the coal width between the working face and the abandoned roadway is 3.45 m, a crack in the rock strata with a height of approximately 22 m above the edge of the abandoned roadway in front of the working face is clearly observed, and the dip angle of the crack is approximately 54°, as shown in Figure 4(a). The roof of the overlying strata in the goaf behind the working face collapses continuously,

FIGURE 1: The distribution of abandoned roadway in the working face. ① and ②—abandoned roadway; 1—haulage roadway; 2—ventilation roadway; 3—30106 working face; 4—coal.

FIGURE 2: The experiment device. 1—displacement measuring point; 2—abandoned roadway; 3—advancing direction of working face.

FIGURE 3: Testing system.

the range of mining influence increases, and the slope phenomenon appears in the coal on the right side of the goaf.

When the working face is connected with the abandoned roadway, as shown in Figure 4(b), the cracks above the abandoned roadway continue to expand, almost passing through the separated strata above the abandoned roadway. Under the action of the pressure of the overlying strata, the basic top strata break ahead and form a very large “rock mass” above the abandoned roadway in front of the working face, the coal edge in front of the abandoned roadway is the hinge point of the rotation and subsidence, and the collapsed strata in the goaf behind the working face are gradually compacted.

2.3.2. Variation Law of the Rock Displacement. The arrangement of rock displacement measuring points is shown in Figure 5, and representative measuring points 1, 2, 3, and 4 are selected to study the displacement characteristics of the overlying strata. Among them, measuring points 1 and 2

are arranged behind the abandoned roadway, and measuring points 3 and 4 are arranged in front of the abandoned roadway, 6 m from the edge of the abandoned roadway. Measuring points 1 and 3 are located in the 5 m strata of the coal seam roof, and points 2 and 4 are located in the 15 m strata of the coal seam roof.

The change characteristics of rock displacement in the process of mining and passing through the abandoned roadway in the working face are shown in Figure 6. The origin of the abscissa of the figure is the edge of the abandoned roadway. With the advance of the working face, the displacement of the overlying strata increases gradually. When the working face is about to pass through the abandoned roadway, the displacement of measuring points 1 and 2 of the overlying strata behind the abandoned roadway increases by 2.85 m and 2.18 m, respectively, and the displacement of measuring points 3 and 4 of the overlying strata in front of the abandoned roadway increases by 0.12 m and 0.26 m, respectively. After entering the abandoned area, with the advance of the working face, the displacement of the overlying strata increases slightly, and measuring points 1 and 2 are 0.36 m and 0.12 m, respectively. The displacements of measuring points 3 and 4 remain approximately zero.

2.3.3. The Stress Distribution Law of the Surrounding Rock. Stress measuring points 5 and 6 are arranged in the coal seam on both sides of the abandoned roadway, and the arrangement of the stress measuring points in the rock strata is the same as that of the displacement measuring points, as shown in Figure 5. The stress change curve of the surrounding rock is obtained, as shown in Figure 7.

For measuring points 1, 2, and 5 behind the abandoned roadway, the stress increases gradually with the advance of the working face. As the working face advances forward, the stresses at measuring points 1, 2, and 5 increase gradually and reach peak values of 11.1 MPa, 10.25 MPa, and 13.35 MPa, respectively. Then, as the working face continues to advance, the stress gradually decreases, and when the working face passes through the abandoned roadway, the stresses at measuring points 1, 2, and 5 are reduced to 2.5 MPa, 2.4 MPa, and 0 MPa, respectively. At measuring points 3, 4, and 6 in front of the abandoned roadway, the stress increases gradually with the advance of the working face. When the coal between the working face and the abandoned roadway is about to be run through, the stresses at measuring points 3, 4, and 6 reach the peak values of 8.37 MPa, 7.6 MPa, and 9.16 MPa, respectively. Once the abandoned roadway is passed, the stress at every measuring point remains basically unchanged.

2.3.4. Characteristics of the Working Resistance of Hydraulic Support When the Working Face Passes through an Abandoned Roadway. As the distance between the working face and the abandoned roadway gradually decreases, the working resistance of the hydraulic support increases gradually, and when the working face is about to pass through the abandoned roadway, the resistance value reaches its maximum. After entering the abandoned roadway, the working

FIGURE 4: The deformation of the overlying strata in the model. (a) The width of coal between the working face and abandoned roadway is 3.45 m. (b) The working face is connected with the roof caving area. 1—crack width increased; 2—rotary subsidence of rock block.

FIGURE 5: Measuring point locations. I—abandoned roadway; II—coal; III—advance direction.

FIGURE 6: The variation in displacement at the measuring points.

resistance of the support decreases rapidly and tends to be stable, as shown in Figure 8. When the working face is 4.2 m from the abandoned roadway, the working resistance of the support is 8102 kN. When the working face is about to pass through the abandoned roadway, the working resistance of the support reaches the peak value of 12046 kN. After the working face enters the abandoned roadway, the average working resistance of the support is 3142 kN. The reason for this result is that with the advance of the working face, the coal between the working face and the abandoned roadway becomes narrow and gradually loses its bearing capacity; the load of the overlying strata is basically borne by the hydraulic support, and the resistance of the support increases sharply. When the working face passes through the abandoned roadway, the fractured rock mass on the

working face rotates and falls into the goaf, resulting in a dynamic pressure load, causing the working resistance of hydraulic support to peak. After entering the abandoned roadway, as the release of rock stress, the support only bears the weight of the bulk rock, so the working resistance of the support is small.

3. Relationship between the Support and Surrounding Rock in the Working Face

3.1. Fracture Characteristics of the Stope Roof. With the advance of the working face, the width of the coal between the working face and the abandoned roadway gradually decreases, the narrower coal becomes unstable and is ultimately destroyed, losing its supporting capacity under the action of leading abutment pressure, and the coal is exposed at the front edge of the abandoned roadway. At this time, the overlying strata of the coal seam are in a cantilever state at the front edge of the abandoned roadway, and under the action of mine pressure, the cantilever structure breaks at this position, forming a rock block B with a hinge structure, which rotates and subsides, as shown in Figure 9.

3.2. Determination of the Working Resistance of the Support. When the working face is about to pass through the abandoned roadway, as shown in Figure 9, fault rock block B will rotate into the goaf, with the center of the fracture line, which can be simplified in a mechanical calculation model, as shown in Figure 10.

Under the combined action of the basic overhanging self-weight Q_2 , the additional force F of the overlying

FIGURE 8: Support working resistance curve of the working face through the abandoned roadway.

bedrock near the fault line and the unbroken basic roof in front, the additional force F' of the broken soft rock behind the roof, and the direct roof weight Q_1 , the strata rotates and subsides.

To prevent the damage caused by bench subsidence and rotation of the fractured rock mass in the working face, at this time, the resistance P_0 provided by the hydraulic support to the direct roof through the top coal is as follows:

$$P_0 = Q_1 + Q_2 + F'. \quad (1)$$

As the separation occurs behind the roof, as long as the broken soft rock acts on the roof, F' is small and can be ignored, that is

$$P_0 = Q_1 + Q_2. \quad (2)$$

P_0 is simplified as a concentrated force; O' is the action position in the middle of the hydraulic column; L_{K1} is the horizontal distance from the coal wall, m. For the roof fracture point O , the moment balance can be obtained:

$$\frac{B+X+L}{2}Q_2 + Q_1 \frac{X+L_1+B}{2} = P_0(B+X+L_{k1}). \quad (3)$$

FIGURE 9: Basic roof breakage characteristics. 1—coal; 2—advance direction; 3—working face; 4—goaf.

FIGURE 10: Support load calculation chart. 1—abandoned roadway, 2—coal, 3—working face, 4—fracture position.

Therefore,

$$P_0 = \left(\frac{B + X + L}{2B + 2X + 2L_{K1}} \right) Q_2 + \left(\frac{X + L_1 + B}{2B + 2X + 2L_{K1}} \right) Q_1. \quad (4)$$

P_0 is provided by the support through the top coal, and because the top coal itself has no supporting capacity, the support needs to bear P_0 and the top coal gravity Q_3 , that is

$$P = P_0 + Q_3. \quad (5)$$

Among them,

$$Q_3 = KL_K h_1 \gamma_1. \quad (6)$$

In addition, when the working face is about to pass through with the abandoned roadway, the direct roof above the abandoned roadway is close to collapsing, and the self-weight Q_1 of the direct top is

$$Q_1 = K(X + L)h\gamma. \quad (7)$$

The direct roof self-weight Q_2 can be expressed as

$$Q_2 = K(X + L + B)h_2\gamma. \quad (8)$$

FIGURE 11: Numerical model.

Then, the support load of hydraulic support P is

$$P = KL_K h_1 \gamma_1 + \left(\frac{B + X + L}{2B + 2X + 2L_{K1}} \right) (L + X + B) K h_2 \gamma + \left(\frac{X + L_1 + B}{2B + 2X + 2L_{K1}} \right) (X + L) K h \gamma. \quad (9)$$

In the formula, h is the thickness of the direct roof fracture, m; h_1 is the thickness of the top coal, m; h_2 is the thickness of the basic roof, m; B is the width of the abandoned roadway, m; X is the width of the coal between the working face and the abandoned roadway, m; K is the width of the hydraulic support, m; L_{K1} is the distance from the central point of the hydraulic support force to the coal wall, m; L_K is the length of the top coal controlled by the hydraulic support, m; γ is the bulk density of the roof strata, kN/m^3 ; γ_1 is the bulk density of the top coal, kN/m^3 ; and L is the periodic weighting step length, 10–15 m.

Among them [16],

$$L = L_1 + L_2, \quad (10)$$

$$L_1/L_2 = 0.5 \sim 0.7.$$

The working face passes through the abandoned roadway. Due to the increase in the range of the abandoned roof, with this mining method, the separation height of the overlying strata is greater than that with normal mining, which leads to the corresponding increase in the fracture height of the roof. Assuming $h_2 = 22$ m, determined by a similar simulation test, $\gamma = 22.54 \text{ kN/m}^3$, $\gamma_1 = 14 \text{ kN/m}^3$, $L = 10$ m, $L_{K1} = 3.5$ m, $L_K = 5.5$ m, $B = 8$ m, $h = 5$ m, $h_1 = 3.2$ m, and $X = 0 - 3$ m, equation (9) obtains $P = 11724 \sim 12812 \text{ kN}$, which is close to the results of similar simulation experiments.

4. Numerical Simulation

4.1. Numerical Model and Schemes. The middle plane of the working face is taken as an example of establishing a plane model by using 3DEC, as shown in Figure 11. The model is 120 m long and 52 m tall, with a total of 1 575 blocks and

19 344 zones. The bottom of the model is fixed in all directions, the normal displacements of the lateral boundaries are limited, and the top of the model uses a stress boundary to simulate the overlying strata weight. The in situ stress is generated according to the in situ measured values. The rock mass, backfill, and joints are calculated by using the M-C constitutive model. The stress-strain curve of a pressed block determined by using the M-C model is similar to the working condition of a hydraulic support, so a checked block is adopted to simulate the hydraulic support. The material parameters in the model are shown in Table 1.

First, the abandoned roadway (8 m wide and 6 m high) is excavated, and the equilibrium state before the working face excavation is calculated. Then, the schemes with no backfilling and different backfill strengths (uniaxial compressive strength (UCS) = 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 MPa) are simulated independently. FISH language is used to control the excavation of the working face.

4.2. Effects of Backfill. By comparing the schemes of with no backfilling and a backfill strength of UCS = 2.0 MPa, the effects of the backfill are analyzed. The moment when the working face excavation exposes the abandoned roadway is analyzed. The plastic zone, stress tensor of the surrounding rock, and hydraulic support deformation of each scheme are shown in Figures 12–14, respectively.

According to Figure 12, if the abandoned roadway is not filled, the plastic zone will extend to a large area of coal in front of the abandoned roadway. After filling, although the plastic zone extends to the backfill, the size of the plastic zone of the coal seam in front of the abandoned roadway decreases gradually because the filling material supports the roof.

According to Figure 13, without backfill, the immediate roof collapses and fills the abandoned roadway, but its bearing capacity is very small. The stress is transferred to both sides of the abandoned roadway, which leads to a significant stress concentration in the coal in front of the abandoned roadway. The pressure of the hydraulic support on the floor then increases (this indicates that the force on the hydraulic support increases). After filling, the stress concentration on both sides of the abandoned roadway is weakened, and the

TABLE 1: Material parameters in the numerical simulation.

Strata	Thickness/m	Young's modulus/GPa	Poisson's ratio	Tensile strength/MPa	Cohesion/MPa	Friction angle/°
Pack sand	10.0	15.2	0.21	2.7	9.2	29
Sandy mudstone	9.0	7.5	0.25	0.9	3.6	26
Pack sand	12.0	17.1	0.17	3.9	7.1	29
Mudstone	5.0	9.2	0.22	1.3	3.7	21
Coal seam	6.0	6.7	0.19	0.7	2.9	23
Siltstone	10.0	12.9	0.27	1.5	5.6	25

FIGURE 12: Plastic zone of the surrounding rock.

pressure of the hydraulic support on the floor is greatly reduced (which indicates that the force on the hydraulic support is greatly reduced).

Figure 14 shows that without filling, the pressure transferred from the abandoned roadway to the hydraulic support causes it to deform significantly, characterized by the shrinkage ΔS of the front column being significantly greater than that of the back column, up to 57 cm, and the support stability being greatly reduced. After filling, the shrinkage ΔS of the front column is still greater than that of the back column but significantly reduces to 8 cm, which has almost no impact on the support stability.

4.3. Effect of Backfill Strength on Shrinkage of the Front Column of the Hydraulic Support. The shrinkage ΔS of the front column of the hydraulic support of each scheme is recorded. The results are shown in Figure 15.

As shown in Figure 15, with an increase in backfill UCS, the shrinkage ΔS of the front column of the support decreases continuously, but the reduction rate also decreases. When the backfill UCS > 2.0 MPa, ΔS no longer decreases; that is, the stability of the support no longer increases.

In summary, filling the abandoned roadway can reduce the size of the plastic zone in the coal, decrease the pressure on the hydraulic support, and improve the support stability. However, when the filling strength increases to a certain value, these effects are no longer enhanced. Therefore, considering the cost, the backfill with UCS = 2.0 MPa should be selected on-site.

5. Engineering Application

5.1. Engineering Geological Conditions. The length of the 30106 transport roadway is 648.5 m, the length of the ventilation roadway is 626.3 m, the length of the working face is 124–160 m, the average length is 142 m, and the recoverable length is 600 m. The fully mechanized top coal caving technology is adopted: the coal cutting height is 2.8 m, the coal caving height is 3.2 m, the mining and caving ratio is 1 : 1.17, the support type is ZF4800/17/33, the shearer cutting depth is 0.60 m, and the daily progress is 2.4 m. The abandoned roadway and working face intersect at 90°. The length, width, and height of the abandoned roadway are 35 m, 8 m, and 6 m, respectively. When the working face passes through the abandoned area, filling with high water material is adopted.

5.2. Filling Process. The filling process adopts open filling with high water material. First, the coal blocks are packed into woven bags at both sides of the abandoned roadway, and 1.5 m wide coal walls are built with the woven bags of coal. Then, the grouting pipe is inserted into the woven bags of the coal wall, the mortar is injected with a water-cement ratio of 0.5 : 1, and 5% accelerant is added to solidify the coal wall. In the construction of the coal wall, it is not closed to facilitate the transportation of filling slurry; at the same time, it is easy to check the filling situation. With the gradual increase in the filling liquid level, the isolation wall is gradually raised until closed, and filling is stopped when the filling pressure is 2 MPa. The water-

FIGURE 13: Stress tensor of the surrounding rock.

FIGURE 14: Deformation of the hydraulic support.

FIGURE 15: Shrinkage ΔS of front column versus backfill UCS.

cement ratio of the high water material is 5.2:1. After filling, the solidification strength reaches 70% of the final strength of the material for seven days, and the final strength is 2 MPa.

5.3. Analysis of Filling Effect. After filling, the working face successfully passes through the abandoned roadway by reducing the mining height, moving the support in time,

increasing the advancing speed, and so on, as shown in Figure 16. In this process, mine pressure observations are carried out, and the measured average working resistance curve of the support is obtained, as shown in Figure 17.

- (1) It can be seen from Figure 17 that the working resistance of the support increases at first and then decreases as the working face approaches and then passes the abandoned roadway, and the working resistance of the support in the mining process is 2908-4504 kN, which is still slightly greater than the normal mining resistance value. This is due to the adhesion between the material and scattered coal-rock mass, the connection of the dense roof, and the large compression deformation of the filling body during filling
- (2) In the process of the working face passing through the abandoned roadway, the integrity of the filling body is good, and there are no phenomena such as roof fall, coal pillar slope, or gas accumulation. The mining stress can be transferred in the filling body, the support does not have an impact load, the mine pressure behavior is alleviated, and the working face passes through the abandoned roadway safely

FIGURE 16: The working face passes through the abandoned roadway.

FIGURE 17: Average load curve of the support working through abandoned roadways.

6. Conclusion

- (1) When the plastic zone of the coal extends between the working face and the abandoned roadway, the roof of the overlying strata breaks at the edge of the coal in front of the abandoned roadway and rotates downward
- (2) The working resistance of the hydraulic support increases gradually with the decrease in the coal width between the working face and the abandoned roadway, and the working resistance of the hydraulic support reaches the peak value when the plastic zone of the coal runs through, which is 3-4 times the working resistance of the hydraulic support during normal mining
- (3) The mechanical model of the surrounding rock and support is established, and the formula for calculating the working resistance P of the support when the working face crosses the abandoned roadway is derived. When crossing the abandoned roadway, $P = 11724 \sim 12812$ kN
- (4) When the working face excavation exposes the abandoned roadway, the front column of the hydraulic support compacts sharply, and the shrinkage is significantly greater than that of the back column, which leads to a significant decrease in the stability of the

support. The lower shrinkage ΔS of the front column decreases with the increase in the backfill UCS, but ΔS basically stabilizes when the backfilling UCS > 2.0 MPa

- (5) Engineering application results show that after filling the roadway using a high water material with UCS = 2.0 MPa, the dangers of leakage in front of the support and impact load caused by early fracturing of the roof are eliminated, the appearance of ground pressure is alleviated, and the working face crosses the abandoned roadway safely; thus, this work provides a theoretical basis and application guidance for working faces crossing abandoned roadways

Abbreviations

- F : The additional force of the overlying bedrock near the fault line (kN)
 F' : The additional force of the broken soft rock behind the roof (kN)
 Q_1 : The self-weight of the direct roof (kN)
 Q_2 : The self-weight under combined action of the basic overhanging (kN)
 Q_3 : The gravity of the top coal (kN)
 P_0 : The resistance provided by the hydraulic support to the direct roof through the top coal (kN)
 h : The thickness of the direct roof fracture (m)
 h_1 : The thickness of the top coal (m)
 h_2 : The thickness of the basic roof fracture (m)
 B : The width of the empty roadway (m)
 K : The width of the hydraulic support (m)
 X : The width of the coal between the working face and the empty roadway (m)
 L_{K1} : The distance from the central point of the hydraulic support force to the coal wall (m)
 L_K : The length of the top coal controlled by the hydraulic support (m)
 γ : The bulk density of the roof strata (kN/m^3)
 γ_1 : The bulk density of the top coal (kN/m^3)
 L : Periodic weighting step (m)
 P : The support load (kN)

Data Availability

All data used to support the study is included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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