Research Article

Study on the Bearing Characteristics and Application of the Filling Body in Original Roadway Filling and Nonpillar Driving

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1. Introduction
As the depth of coal mining in China increases, deep roadways will be affected by the superimposed stress of large buried depth, tectonic deformation, and uneven mining, which cause difficulties in roadway maintenance and in continuous mining replacement in the stope [1]. Moreover, the coal recovery rate is greatly reduced by the retention of various coal pillars during mining, which results in a large waste of resources [2, 3]. Considering the low recovery rate of resources and the difficulty in the replacement of the stope, a new method for roadway layout and driving, i.e., the original roadway filling and nonpillar driving (ORFNPD) technology, is adopted in the Huainan mining area, China. In ORFNPD, filling materials are used to fill the abandoned groove in the gob. After the filling body stabilizes, the return airway in the lower section is directly excavated along the edge of the filling body. In this way, the newly excavated roadways do not have to be disturbed by mining twice, which effectively improves the maintenance state of the gob-side roadway and realizes rapid continuous mining without a coal pillar in the pressure relief protective seam. The successful application of the roadway layout and driving method is attributed to the stable bearing structure formed by the filling body and the roof and floor of the original roadway. Such a structure can protect the newly excavated roadway [4, 5]. It can be known that the bearing characteristics of the filling body have an important influence on...
the stability of the surrounding rock in the return airway in the lower section. Therefore, studies on the mechanical properties of the original roadway filling body can lay a foundation for the wide application of the ORFNPD technology to deep mining.

At present, widely adopted filling technologies in coal mining mainly include gob filling to control surface subsidence and roadway-side filling in gob-side entry retaining (GSER). Since roadway-side filling body is an important part of the bearing system of GSER surrounding rock, its stability characteristics keep attracting the attention of scholars all over the world. Yilmaz and Sadeler [6] studied the drainage consolidation process of slurry with different components through laboratory tests and explored the variations of working performance, consolidation performance, and shear strength of slurry after consolidation. Yan et al. [7] established a prediction model for the ratios of filling materials through a neural network technology and contrasted the predicted results of the model with the actual values. Bi et al. [8] explored the influences of mass concentration of the filling material and water-cement ratio on the slump degree, water content, and uniaxial compressive strength of the filling paste through orthogonal test and determined the reasonable proportions of the filling material under corresponding conditions. Huang et al. [9] studied the characteristics and limitations of different filling methods such as cemented filling and evaluated the filling effect with reference to the typical filling and mining practice. Kong et al. [10] simulated and analyzed the influence of filling materials with a high water content on the long-term stability of gypsum column as well as the hydrogeological response characteristics of stope filling. Kanan and Karanfil [11] contrastively analyzed the influence characteristics of shear resistance strength, tensile strength, and spatial restriction of different filling materials on the stability of coal pillars. According to the strength characteristics and compaction characteristics of different filling materials, Ning et al. [12] pointed out that the compactness and filling rate of filling materials were the key factors affecting the subsidence of overlying strata. Based on the deformation characteristics of roadway surrounding rock and the mechanism of roadway-side support, Qi et al. [13] deduced a calculation formula for the width of the road-side support. Huang et al. [14] studied the bearing characteristics of underground filling body and the support strength of the working face. Sun et al. [15] analyzed the technical difficulties and key points in construction of solid filling mining support. Zhou et al. [16] proposed a collaborative support system of “filling body + coal pillars + bearing strata” and the conditions for stability. Zhang and Li [17] analyzed the influence of deformation and failure process of weak structure on roof stability by taking the collaborative structure of nonuniformly loaded filling body and roadway-side compound support as the mechanical model. Liu et al. [18] explored the technology of isolated and separated grouting filling in overlying strata, and the bearing structure jointly formed by filling materials in the separation area, key strata, and coal pillars for partition isolation effectively alleviated land subsidence. Jie et al. [19] systematically studied the interaction mechanism between roof and filling body of GSER and the stability of cemented and solidified filling body of caving gangue. The deformation and failure mode of roadway surrounding rock can hardly be truly observed through theoretical analysis and field measurement, but numerical simulation can faithfully reflect the basic mechanical deformation characteristics of roadway surrounding rock. Li et al. [2] determined the design principle of the filling support resistance by establishing the numerical model of filling support resistance and compression. By numerically simulating the backfill support resistance, He et al. [20, 21] and Beaven et al. [22, 23] analyzed the factors influencing the surrounding rock deformation of gob-side roadway in the fully mechanized top coal caving face and studied the interaction mechanism between surrounding rock and backfill. Rowe [24] explored the relationship between roof separation and roof deformation, obtained the critical value of roof separation, and put forward the technology of “concrete filling on the roadway side + anchor-mesh-cable combined support in the roadway + anchor cable reinforcement on the roadway side”. Zhou et al. [25] established a mechanical model of the key block and the immediate roof, analyzed the mechanism of interaction between the key block and the roadway surrounding rock, and held that the width of the filling body had a great influence on the stability of gob-side roadway. He et al. [26] studied the deformation characteristics of fully mechanized caving roadways through similar simulation tests and pointed out that the filling body should be of both a certain strength and a certain deformation resistance capacity. In summary, research results are mainly focused on the ratio of filling materials, the mechanical properties, and the bearing stability of filling body in GSER. The roadway-side filling body and the original roadway filling body are the main structures that support roof and separate the gob.

The present study focuses on the bearing characteristics of the filling body and the interaction between the filling body and the surrounding rock. The construction of the filling body roadway can not only effectively improve the stress condition of the surrounding rock of the whole roadway, but also provide more support for the surrounding rock of the roadway roof. The research results can provide important reference for the application of the ORFNPD technology.

2. Mechanical Properties of the Filling Body in ORFNPD

2.1. Mechanical Model of the Filling Body. The distribution of abutment pressure in a coal seam, a key factor to determine the mechanical state and failure characteristics of coal, has a direct influence on the stability of roadway surrounding rock during roadway layout. The original roadway filling improves the abutment pressure distribution around the stope [27, 28]. Therefore, it is necessary to analyze the abutment pressure distribution of the filling body on the solid coal side after original roadway filling. The schematic diagram of the inclined stope structure is given in Figure 1.

With the advancement of the working face, the main roof gradually presents a suspended and exposed state. According to the thin plate theory, the main roof of the
gob before collapse can be regarded as a thin plate structure (Figure 2). The differential equation of the elastic curved surface of thin plate is as follows:

$$DV^4w = q$$ (1)

where $D$ is the bending stiffness of the main roof, $D = (Eh^3)/(12(1 - \mu^2))$, Nm; $h$ is the thickness of the main roof, m; $E$ is the elastic modulus of the main roof, MPa; $\mu$ is Poisson’s ratio of the main roof; $w$ is the deflection of the main roof, mm; and $q$ is the load borne by the main roof, MPa.

The internal force per unit width on the cross-section of the thin plate is as follows:

$$M_x = -D\left(\frac{\partial^2 w}{\partial x^2} + \mu \frac{\partial^2 w}{\partial y^2}\right); M_y = -D\left(\frac{\partial^2 w}{\partial y^2} + \mu \frac{\partial^2 w}{\partial x^2}\right); \tau_{xy} = -D(1 - \mu) \frac{\partial^2 w}{\partial x \partial y}$$

$$F_x = -D\frac{\partial}{\partial x} \nabla^2 w; F_y = -D\frac{\partial}{\partial y} \nabla^2 w$$

(2)

The relationship between the stress component and load is as follows:

$$\sigma_x = \frac{12M_x}{h^3} z; \sigma_y = \frac{12M_y}{h^3} x; \sigma_z = -2q\left(\frac{1}{2} - \frac{z^2}{h^2}\right)^2 \left(1 + \frac{z}{h}\right)$$

$$\tau_{xy} = \frac{12M_{xy}}{h^3} z; \tau_{xz} = \frac{6F_z}{h^3} \left(\frac{h^2}{4} - z^2\right); \tau_{yz} = \frac{6F_y}{h^3} \left(\frac{h^2}{4} - z^2\right)$$

(3)

The bending and fracture of the main roof forms key block B, and it begins to rotate and sink. Under the joint action of caving gangue in the gob, original roadway filling body, immediate roof, and coal side, it forms a “large structure” hinged with key blocks A and C (Figure 3). According to equations (2) and (3), the bending deflection of the immediate roof is related to its load; the early strength of the filling body directly influences the fracture of the immediate roof. If the filling body is of sufficient early strength, the immediate roof will first fracture at C, because the rock beam BC under the roof is in a condition of fixed support boundary and has a certain self-supporting ability. Then, the secondary fracture of the immediate roof occurs at B. If the original roadway filling body occurs to insufficient early strength, the immediate roof may fracture at both B and C.

The rotation and sinking of key block B will act on the lower coal side and filling body. Ignoring the influence of the fracture angle of the immediate roof, the simplified mechanical model of the immediate roof is given in Figure 3.

The supporting force $F_s$ of coal side is as follows:

$$F_s = \left(\frac{c}{\tan \phi} + \frac{p_s}{A}\right) e^{\frac{z}{\tan \phi}} - \frac{c}{\tan \phi}$$ (4)

The rotating torques of $F_{H}$, $F_s$, and $F_z$ acting on key block B are as follows:

$$R_H = F_{H}(x_0 + a_1 + b_1)/2$$

$$R_S = \int_{x_0}^{x_0+a_1} f_z \left[-\frac{2}{\tan \alpha} \right] (x - L_1) dx$$

$$R_z = \int_{x_0}^{x_0+a_1} f_z \left[-\frac{2}{\tan \alpha} \right] (x - L_1) dx$$

(5)

According to $\sum M = 0$,

$$F_M = 2(2R_2 + R_3 + M_B - R_{H})$$

(6)
When key block B rotates and sinks (Figure 3), the contact length \( s \) between key blocks A and C to key block B is in the form:

\[
s = \frac{1}{2} \left( h - \frac{L_i}{2} \sin \theta \right)
\]

(7)

\[\sum M = 0, \text{ then } -T_1 (\Delta + (s/2)) + T_2 (h - (s/2)) + R_M + R_G - F_z (L_i/3) = 0. \]

Therefore, the horizontal force of key block A acting on key block B is the following:

\[
T_{AB} = \frac{4FzLi - 12(R_M + R_G)}{3(2h - L_i \sin \theta)}
\]

(8)

The horizontal force of key block C acting on key block B is as follows:

\[
T_{CB} = \frac{2FzLi - 6(R_M + R_G)}{3(2h - L_i \sin \theta) \cos \alpha}
\]

(9)

The rotational moment is calculated from the force on key block B. According to \( \sum M_{EF} = 0 \), the vertical shear forces \( F_{CB} \) and \( F_{AB} \) of key block B can be obtained:

\[
2F_{CB} \frac{L_i \cos \theta}{2} + Fz \frac{L_i \cos \theta}{3} - R_M - R_G + R_{f_c}
- 2T_{CB} \left( h - s - \frac{L_i \sin \theta}{2} \right) \cos \alpha = 0
\]

(10)

According to the “S-R” stability theory of masonry beam structure, the stability of key block B is controlled by key blocks A and C. A small angle may cause a sliding instability of key block B, and an increasing angle may lead to an instability of extrusion deformation. To prevent the above two types of instability:

(1) Coefficient \( K_1 \) of sliding instability is given:

\[
K_1 = \frac{3(2h - L_i \sin \theta)F_{AB}}{4FzL_i - 12(R_M + R_G - R_{f_c})} \tan (\varphi - \beta)
\]

(11)

(2) Coefficient \( K_2 \) of extrusion deformation instability is given:

\[
K_2 = \frac{4FzL_i - 12(R_M + R_G - R_{f_c})}{3(2h - L_i \sin \theta) \tan \alpha}
\]

(12)

In the initial stage of the original roadway filling, the filling body is in the initial setting stage and is of low strength; the key blocks have not completely touched the gangue; and the caving gangue in the gob corresponds to a small supporting force. At this moment, if the key blocks are unstable, the filling body will bear great stress and is likely to be crushed. Therefore, it is important to maintain the stability of key blocks at the end of the working face during the original roadway filling. Considering the actual conditions of the 62310 working face, the relationship between the instability coefficients \( K_1 \) and \( K_2 \) of key blocks and the support resistance of the filling body \( F_{d} \) is obtained (Figure 4). It takes time for the filling body to realize bearing stability, so the original roadway filling body is of small bearing capacity in the early stage, and is affected by the initial collapse or periodic collapse of the main roof. Therefore, the support resistance of the filling body is taken as the strength of 1-day age, and the early strength of the original roadway filling body exerts great influence on the stability of key blocks.

With the further recovery of the working face, the stratum-by-stratum collapse of roof from bottom to top and the roof separation increase continuously, and the residual boundary of the collapsed strata changes from the bearing state to the loading state [29, 30]. When the residual boundary of the main roof reaches the ultimate bearing capacity, it will swing and subside to the gob side, resulting in increased pressure and severe deformation of the roadway surrounding rock [31–33]. If the filling body support has sufficient support strength and stiffness during mining, it can cut off the immediate roof, key block B and key block...
A on the solid coal side in the process of “active collapse” of the roof rock. Meanwhile, key block C on the gob side forms an articulated structure. Accordingly, in order to protect the roadway in the lower section, the filling body needs to have strong bearing capacity which enables it to timely bear the stress load caused by roof subsidence and adapt to roof rotation subsidence. With the sequential replacement of nonpillar mining in the working face, only the filling body in the large gob formed by mining in the upper and lower working faces undertakes the roof and floor, and the filling body still supports key block B and the overburden stress above it. A new high stress concentration area will be formed within the bearing range of the filling body. To avoid the impact of high stress concentration on the underlying coal seam, the filling body should have the characteristics of long-term weakening disintegration.

3. Experiment on Mechanical Characteristics of Filling Materials

3.1. Experimental Materials and Methods. Rapid solidification materials with a high water content were selected as materials for original roadway filling in the onsite application. They were composed of sulphaloamine cement clinker (material A) and sand which was rich in aluminium silicate and silicon fluoride (hardening agent) (material B), respectively. The mixture filling body boosts good cementation performance, high early strength and strong bearing capacity. In addition, single slurries of material A and material B do not coagulate in 24 h, yet the mixture coagulates and hardens quickly.

Materials A and B were mixed with water at 1 : 1, 1.5 : 1, 2 : 1, 2.5 : 1, and 3 : 1, respectively, to make single slurries, and then the single-material slurries of materials A and B were mixed, fully stirred and placed in the experimental mold (1,000 mm × 500 mm × 150 mm) until condensation. Next, the test blocks were placed in the maintenance box. After the blocks reached their corresponding ages, they were processed into standard cylinder specimens (diameter × height = 50 mm × 100 mm) by the rock coring machine and the grinding machine. Subsequently, they underwent strength test by the RMT rock servo tester. The loading rate was 0.01 mm/s, and three blocks were tested at one age for average values. The test flow chart is shown in Figure 5.

4. Analysis on the Results of the Ratio Test for Original Roadway Filling Material

Uniaxial compressive strength is one of the most commonly adopted indexes to evaluate the mechanical properties of the filling body. The RMT rock mechanics test system was used, and the specific loading process is shown in Figure 6.

4.1. Early Strength Characteristics of the Filling Body. The variations of the strength of the filling paste at different ages were analyzed. Uniaxial compressive strength tests were conducted on the filling specimens in the age range of 2-48 h at different water-cement ratios (1 : 1, 1.5 : 1, 2 : 1, 2.5 : 1, and 3 : 1) (Figure 7). The strengths of the filling body made of rapid solidification material with a high water content were 1.12 MPa, 0.93 MPa, 0.57 MPa, 0.33 MPa, and 0.21 MPa at 2 h and 5.63 MPa, 4.66 MPa, 2.87 MPa, 1.65 MPa, and 1.02 MPa at 48 h, respectively, increasing early five times within 2 d. According to the Standard of Chinese Coal Industry (MTT 420-1995) [34–38], this type of high-water-content material has good early strength; it can generate the initial support for roof in time, control the deformation of surrounding rock, and guarantee the stability of the original roadway filling. With respect to different water-cement ratios at the same age, a higher/lower water-cement ratio leads to a lower/higher strength of the filling body. This demonstrates that comprehensive consideration should be given to the economic factors and adaptability of the filling material in onsite application.

4.2. Stability and Bearing Characteristics of the Filling Body. Figure 8 shows the variations of uniaxial compressive strength of the specimens in the age range of 2-30 d at different water-cement ratios (1 : 1, 1.5 : 1, 2 : 1, 2.5 : 1, and 3 : 1). It can be seen that the specimens all experience a compaction stage, an elastic stage, a fracture stage and a failure stage. For example, at 2 d, 5 d, and 7 d, the specimen with a water-cement ratio of 2 : 1 corresponds to strengths of 2.87 MPa, 5.37 MPa, and 6.60 MPa, respectively, and its axial strains are 5.83 × 10⁻³, 8.17 × 10⁻³, and 9.39 × 10⁻³, respectively. With the increase in the uniaxial compressive strength, the bearing capacity for deformation of the filling specimen jumps, which allows a greater deformation. This suggests that when the filling body is affected by the superposition of abutment pressure caused by working face
Material A
Mix well until it condenses
Coring
Material mixing
Standard samples
RMT rock mechanics test system
Figure 5: Flow chart of the test.

Material B

Figure 6: Process of the filling specimens.

Figure 7: Variation curves of uniaxial compressive strength of the specimens.

- Water-cement ratio 1:1
- Water-cement ratio 2:1
- Water-cement ratio 1.5:1
- Water-cement ratio 2.5:1

Uniaxial compressive strength (MPa) vs. Time (h)
recovery, the filling body of the original roadway can adapt itself to the roof subsidence by increasing the deformation, and then it forms a stable structure with the roof and floor strata to meet the requirements of recovery.

Figure 9 is the variations of the uniaxial compressive strength of specimens in 30 d. The strength of the filling specimens jumps in the age of 0-7 d, and gradually stabilizes after 7 d. The strengths of the filling specimens with different water-cement ratios after 7 d are about 8.12 MPa, 6.91 MPa, 6.60 MPa, 3.95 MPa, and 2.20 MPa, respectively.

4.3. Long-Term Weakening of the Filling Body. Figures 10 and 11 are the variations of the uniaxial compressive strength and water content of the specimens in 1.5 years. According to the strength variations at different water-cement ratios, it can be known that the strengths of the specimens with different water-cement ratios (1:1, 1.5:1, 2:1, 2.5:1, and 3:1) after 1.5 years decline to 3.25 MPa, 2.71 MPa, 2.02 MPa, 1.77 MPa, and 1.39 MPa, respectively. The strengths of the filling specimens also decrease notably, and the water contents fall to 16.68%, 15.49%, 15.04%, 13.62%, and 13.03%, respectively. With the passage of time, the slow loss of water causes damage of different degrees to the internal cementation stability. The higher the water-cement ratio of the specimen is, the more notably the water content decreases, and the more significantly the strength weakens, indicating that the filling specimen features long-term weakening. Under the action of vertical stress of roof and floor strata, the filling body with significant water-loss-induced weakening will break and disintegrate. Resultantly, the roadway is filled with collapsing rock blocks. The sides of solid coal, filling body and caving gangue bear the roof load above the roadway, thus eliminating the stress concentration of the underlying coal seam.
Figure 12: Failure modes of filling specimens with short-term ages.

4.4. Macroscopic Failure Characteristics of the Filling Body. Figures 12 and 13 display the macroscopic failure modes of filling specimens with short and long ages under uniaxial compression, respectively. The short-age filling specimen mainly undergoes shear failure; the fracture block is relatively complete, and the angle between the shear plane and the horizontal plane is about 60°. This indicates that the filling slurry has good workability, uniform texture, and absence of segregation. The entire specimen has consistent macroscopic failure state under uniaxial compression. After fracturing, the long-age specimen generates block and powder of different sizes with notable brittle failure. The reason is that the internal water loss of the filling specimen causes certain changes in the internal structure of the specimen and reduces the cohesion. Finally, it leads to the disintegration macro failure of the filling specimen under load.


5.1. Geological Overview. Xinzhuangzi Coal Mine is located in the west of Huainan City, China, and at the east foot of Bagong Mountain. The mine field stretches from the north side of Huai River to the south side of it. The average strike length and average dip length of the 62210 fully mechanized working face in the mine are 1,285 m and 194 m, respectively. The area of the working face is 249,290 m², and the elevation of working face ranges from −660 m to −770 m. The average thickness of coal seam is 1.0 m, and the dip angle is in the range of 21°−30°, with an average of 25°. The corresponding overlying B11 and B8 coal seams have not been mined in this period. The immediate roof belongs to sandy mudstone which has a thickness of 2−12 m and is of fragile dark-gray thin layer. The main roof is fine sandstone with a thickness of 0-6 m. The immediate floor is fine sandstone which has a thickness of 1-3.5 m and is of fragile gray thick layer. The main floor belongs to mudstone with a thickness of 1-4 m. The schematic diagram of geological overview of the working face is given in Figure 14.

5.2. Numerical Analysis. To analyze the stability characteristics of surrounding rock in ORFNPT and solve practical problems, with the 62210 working face of Xinzhuangzi Coal Mine taken as the background, a calculation model was established by FLAC3D large-scale finite difference software [39, 40]. Some parameters of the model: strike length 320 m, dip length 230 m, height 248 m and average coal seam thickness 1 m. The four sides and bottom of the model were fixed. Besides, a 13.8 MPa vertical stress was applied to the top of the model to simulate the weight of the overlying strata, and the lateral pressure coefficient was 1.0. Table 1 lists the mechanical parameters of coal rock.

The four sides of the model were only a horizontal displacement boundary, and the floor was a fixed boundary. The simulated buried depth of the coal seam ranged from −660 m to −770 m, and a uniformly distributed load was applied to the top boundary of the model. The constitutive relation of roadway surrounding rock followed the modified Mohr-Coulomb criterion (In this paper, the bearing characteristics of filling body are analyzed under the background of deep mining which will arouse strong unloading disturbance in the surrounding rock, especially under the condition of high ground stress. The redistribution of stress field is a dynamic process from dynamic response to static action, so it is appropriate to adopt the modified Mohr Coulomb criterion.) [27–29]. The numerical simulation included two parts: (1) the vertical stress distribution characteristics of roadway surrounding rock in ORFNPT and GSEDSCP and (2) the deformation and displacement characteristics of roadway surrounding rock in ORFNPT and GSEDSCP.

The simulation was conducted using single-factor analysis. The filling parameters of ORFNPD were as follows: the filling width was 3 m, and the filling body strengths were 8.12 MPa, 6.91 MPa, 6.60 MPa, and 2.20 MPa (i.e., water-cement ratios of 1 : 1, 1.5 : 1, 2 : 1, and 3 : 1). The cut surface at 30 m behind the shaft and drifting face, perpendicular to the axis of the roadway, was selected for results analysis.

5.2.1. The Stress Distribution Law of the Surrounding Rock of the Roadway by the Adjacent Working Face. Influenced by the strength of the original roadway filling body, the stress distribution law of the surrounding rock of the excavated roadway differs. When the strengths of the filling body are 8.12 MPa, 6.91 MPa, 6.60 MPa, and 2.20 MPa, respectively, the peak stresses in the solid coal by the excavated roadway are about 33.1 MPa, 33.2 MPa, 34.4 MPa, and 36.86 MPa, respectively; the peak values occur at positions of about 2 m, 2.5 m, 3.5 m, and 3.5 m to the solid coal surface, respectively; and the stress concentration coefficients are about 1.50, 1.51, 1.56, and 1.67, respectively (Figure 15). It can be known that with the increase in the strength of the original roadway filling body, the value of the peak stress in the solid coal by the excavated roadway falls; the position of peak stress is closer to the solid coal roadway side and the stress concentration becomes smaller.

The stress variation curve of the filling body under different filling strengths during roadway excavation along the direction of the roadway is shown in Figure 16. It can be known that under different filling strengths, with the advancement of the excavated working face, the stress of the filling body varies similarly; but at the same position, different filling body strengths correspond to notably different
stress values. As the distance from front of the working face increases, the stress of the filling body surges in the range of 2-20 m, reaching the maximum at about 20 m from front of working face. The stress decreases slightly after 20 m from front of working face, and the stress stabilizes at about 90 m from front of the working face. However, the stress on the filling body at the back of the excavated working face basically does not change. A contrastive analysis on the filling bodies of different strengths reveals that at the same distance from the working face, the stress on the filling body rises with the increase in the filling body strength; and the higher the filling body strength is, the higher the stress on the filling body is. When the strengths of the filling body are 8.12 MPa, 6.91 MPa, 6.60 MPa and 2.20 MPa, respectively, the maximum stresses on the filling body are about 28 MPa, 24.8 MPa, 22.74 MPa and 17.5 MPa, respectively, and the stabilization stresses on the filling body at the back of the excavated working face are about 18 MPa, 15.7 MPa, 14.66 MPa and 11.4 MPa, respectively. It can be known that the original roadway filling body has a typical strength effect, the higher the strength of the filling body is, the higher the stress on the filling body is, thus conducing the stability of the roadway of the next working face.

5.2.2. Distribution Characteristics of Surrounding Rock Displacement of Driving Roadway in the Lower Section.

Under different filling strengths, the surrounding rock displacement of the prepared roadway in the lower section corresponds to basically similar distribution. At the position of about 60 m behind the excavated working face, the surrounding rock of the roadway in the lower section is basically stable, but under the filling body of different
It can be summarized that for ORFNPD, as the strength of the filling body increases, the displacement amounts of the roof and floor of the surrounding rock decreases.

5.2.3. Failure Characteristics of Surrounding Rock of Newly Excavated Roadway under the Filling Body of Different Strengths. According to Figure 18, as the strength of the filling body varies, the failure characteristics of the surrounding rock of the filling roadway vary constantly. The failure of roadway surrounding rock are in the forms of both shear failure and tensile failure, mainly shear failure, and the filling body is in the state of ongoing failure, that is, the filling body is not damaged and unstable. Furthermore, the filling body has not been damaged but is in a state of failure. Besides, as the strength of the filling body rises, the failure range and extent of the surrounding rock fall.

The following conclusions can be drawn based on the comparison of the stress distribution law, displacement distribution characteristics and failure characteristics of roadway surrounding rock in the lower section of driving roadway with different filling strengths. In the ORFNPD technology, the strength of the filling body has a great impact on the stress distribution, deformation and failure characteristics of surrounding rock in the lower section. The stress field, displacement field and failure field are different under different strengths of the filling body. Higher strength of the filling body corresponds to higher stress on the filling body, slighter stress concentration of roadway surrounding rock, the smaller roof-to-floor displacement and milder damage to the surrounding rock. Economic benefits and engineering needs should be comprehensively considered in the decision-making process of specific construction scheme onsite.

6. Onsite Application

6.1. Engineering and Technical Conditions. The 62210 fully mechanized working face of Xinzhuangzi Coal Mine is the working face of B10 coal seam of the second stage in Panel 2 at Level 6. B10 coal seam, the key protective seam for the first mining of coal seam group in Huainan mining area, protects the outburst coal seam in B11b groove upward and the outburst coal seam in B8 groove downward. Moreover, it protects other related coal seams with the aid of drilling and extraction. Parameters of 62210 fully mechanized working face include: average buried depth 715 m; average strike length is the footage of the working face (generally 4 m); and the amount of once filling is about 36 m³.

6.2. Layout and Process of the Filling System. The layout of the ORFNPD system includes the layout of the filling pump station, the laying of the filling pipelines, the construction of the filling template and the preparation and transportation of the filling material (Figure 19).

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### Table 1: Mechanical parameters of coal rock for simulation.

<table>
<thead>
<tr>
<th>Rock name</th>
<th>Rock thickness (m)</th>
<th>Elastic modulus E (GPa)</th>
<th>Poisson’s ratio (μ)</th>
<th>Cohesion C (MPa)</th>
<th>Internal friction angle φ (°)</th>
<th>Tensile strength σt (MPa)</th>
<th>Density d (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mudstone</td>
<td>1.66</td>
<td>22.5</td>
<td>0.22</td>
<td>3.21</td>
<td>39</td>
<td>1.52</td>
<td>2660</td>
</tr>
<tr>
<td>B11a coal</td>
<td>1.07</td>
<td>5.13</td>
<td>0.33</td>
<td>1.15</td>
<td>33</td>
<td>0.14</td>
<td>1387</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>2.7</td>
<td>5.45</td>
<td>0.147</td>
<td>2.16</td>
<td>36</td>
<td>1.3</td>
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The stress distribution law of the roadway surrounding rock by the adjacent working face under the same width and different strengths along the inclination: (a) 8.12 MPa, (b) 6.91 MPa, (c) 6.60 MPa, and (d) 2.20 MPa.

Water-cement ratio (1:1)  Water-cement ratio (2:1)
Water-cement ratio (1.5:1)  Water-cement ratio (3:1)

Figure 16: The stress variation curve of the filling body under different filling strengths during roadway excavation along the direction of the roadway.
Figure 17: Distribution characteristics of the displacement of roadway surrounding rock under filling body of different strengths along the direction of the roadway in the lower section: (a) Variation curves of the vertical displacement of the roadway roof along the direction of the roadway in the lower section; (b) Variation curves of the vertical displacement of the roadway floor along the direction of the roadway in the lower section and (c) Variation curves of the vertical displacement of the solid coal side of the roadway along the direction of the roadway in the lower section.
The process of ORFNPD is as follows: (1) cleaning the floating coal in the floor of the filling roadway, (2) building the filling template-suspending the filling bag and inflating it, (3) stirring the filling material, (4) transmitting the slurry by the double-liquid grouting pump, and (5) filling the filling bag at designated points for solidification.

6.3. Effects of Onsite Filling and Monitoring of the Stress of the Filling Body. Real-time monitoring was conducted on the stress characteristics of the filling body in the 62210 lower groove original roadway by the KJ550 monitoring system for coal mine rock burst. The monitoring system consists of an acquisition monitoring center, a communication network, an onsite stress acquisition device, etc. (Figure 20). The specific monitoring scheme is as follows: Two groups of identical stations were arranged on the filling body of the tail roadway in the 62210 transportation roadway, and stations were located in the longitudinal middle of the filling body. Three stress acquisition instruments (marked as $\sigma$, $\tau$, and $C$) were installed near the solid coal sides, the transverse middle of the filling body and the gob side, respectively. The horizontal distance of the stress acquisition instrument was 0.5 m.

Figure 21 shows the stress variation curve of the original roadway filling body. It can be seen that as the distance from the working face increases, the stress in all parts of the filling body rises first, then falls and gradually stabilizes. The stress in the filling body near the solid coal sides reaches the maximum (about 4.7 MPa) at the position about 22 m away from the working face. Then, with the increase in the distance from the working face, the stress of the filling body keeps decreasing, and gradually stabilizes (about 3 MPa) after the distance reaches about 74 m behind the working face. The stress in the middle of the filling body reaches the maximum (about 5.8 MPa) at position of about 25 m from the working face. Then, with the increase in the distance from the working face, the stress of the filling body declines slowly, and gradually stabilizes (about 5.4 MPa) after the distance reaches about 74 m behind the working face. The stress measured near the gob of the filling body reaches the maximum (about 5.3 MPa) at position of about 22 m from the working face. Afterwards, with the increase in the distance from the
working face, the stress of the filling body continuously declines, and gradually stabilizes (about 4.2 MPa) at position of about 60 m behind the working face.

It can be seen that influenced by the mining of the working face, the stress in the filling body increases first, then decreases and gradually stabilizes. At the same position from the working face, the middle of the filling body has higher stress than the position near gob sides, and the position near the solid coal has the slightest stress, which is generally consistent with the variation of the filling body influenced
7. Conclusions

This study took the recovery and geological conditions of 62210 working face in Xinzhuangzi Coal Mine, Huainan Mining Group, China, as the research object. The mechanical Properties of the original roadway filling body was investigated by the comprehensive research methods of theoretical analysis and laboratory test. Besides, a long-distance transmission of the original roadway filling process was formulated. Furthermore, the stress characteristics and onsite application effect of the original roadway filling body were verified based on the coal mine monitoring data obtained by the KJ550 monitoring system and the test data obtained by onsite filling and sampling. The specific conclusions are as follows.

1. Based on the migration law of the overlying strata, the structural mechanics model of the key strata of ORFNPD is established; the stability criterion of the bearing characteristics of the filling body to the key block is analyzed, and it is clear that the original roadway filling body provides timely initial support to gob roof, which can effectively reduce the surrounding rock deformation and prevent the sliding instability of the key strata. Higher stiffness and strength of the filling body help to adapt itself to the rotary subsidence of the gob roof and protect the roadway in the lower section. Long-term weakening disintegration can effectively avoid the influence of high stress concentration on underlying coal seams.

2. The filling body formed by high water quick-setting materials can effectively meet the needs of the application of the ORFNPD technology. The strength of the filling body is 0.93 MPa at 2 h when the water-to-cement ratio is 2 : 1, and it reaches the peak value (about 6.6 MPa) at about 7 d. The results of onsite filling test show that with the gradual reduction of water content of filling body over a long time, the uniaxial compressive strength drops sharply, and the samples exhibit obvious long-term weakening disintegration failure.

3. In the ORFNPD technology, as the strength of the filling body increases, the stress distribution of the surrounding rock in the lower section becomes more concentrated, and the range of deformation and failure area shrinks. This demonstrates that higher strength of the filling body corresponds to higher stress on the filling body, slighter stress concentration of roadway surrounding rock, the smaller roof-to-floor displacement and milder damage to the surrounding rock. Economic benefits and engineering needs should be comprehensively considered in the decision-making process of specific construction scheme onsite.

4. According to the characteristics of the rapid solidification material with a high water content, the long-
distance transportation of filling was formulated onsite. With reference to the onsite monitoring data, the stress in the filling body increases first, then decreases and gradually stabilizes, which is generally consistent with the variation of the filling body influenced by roof migration in the gob. This fully illustrates that ORFNPD can effectively support the roof and protect the newly excavated roadways in the lower section.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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