

Study on the properties and reasonable width of a phosphogypsum backfill body for gob-side entry retaining in a thick coal seam

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1 **Study on the properties and reasonable width of a**
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16 **Abstract:** This study evaluates the suitability of locally sourced phosphogypsum from Guizhou as a filling
17 material for gob-side entry retaining (GSER) in coal mines. Laboratory tests characterized the material in
18 terms of strength, fluidity, and setting time. The material met the technical requirements for underground
19 filling, and low-alkali conditions combined with a polycarboxylate superplasticizer were more favorable for
20 the application of the phosphogypsum in GSER. For the 11912 working face of a coal mine in Guizhou, the

relationship between filling body strength and width was evaluated using the estimation method and the separated rock block method. Because the estimation method yielded more conservative results, it was adopted for the subsequent sensitivity analysis of various factors affecting filling body strength. Coal seam thickness (h_c) was the most influential factor, followed by n and γ . Filling body width (b_2), roadway width (b_1), lateral pressure coefficient (λ), and internal friction angle between rock blocks (φ_0) also had appreciable effects, whereas the remaining factors were secondary. Theoretical analysis combined with numerical simulation indicated a reasonable roadside backfill body width of approximately 2.0 m. A brief engineering benefit analysis further showed that local phosphogypsum can provide favorable engineering benefits when used as a GSER filling material. These findings can provide a technical basis for its large-scale engineering application.

Keywords: thick coal seam; gob-side entry retaining; local phosphogypsum; roadside backfill body; reasonable width

1. Introduction

Continued socioeconomic development has intensified pressure on coal resources in China, while the limitations of conventional coal pillar retention mining, particularly low resource recovery rates and high safety risks, have become increasingly evident. This has increased the demand for more efficient mining technologies [1]. Gob-side entry retaining (GSER) is one of the most widely applied coal pillar-free mining technologies and can improve coal recovery while reducing resource waste, gaining increasing application and promotion in coal mines [2]. By constructing artificial backfill pillars along the edge of the gob to support the roof, GSER eliminates the need to retain coal pillars and helps maintain the stability of roadways used by subsequent working faces [3]. Stable gob-side roadways are

essential to successful GSER, and the roadside backfill body (RBB) is a key structural component in maintaining this stability [4]. RBB materials must therefore combine suitable fluidity and filling performance with adequate strength, stability, durability, and relatively low production cost to control roof strata movement while retaining the benefits of large-scale engineering application. Conventional RBB materials include hydraulic sand materials [5], gangue materials [6], and paste materials [7]. As GSER technology has developed, increasing emphasis on solid-waste utilization, lower filling costs, and broader technical applicability has promoted the use of high-water filling materials [8] and ultra-high water or paste-like filling materials [9], with favorable social and economic benefits.

Phosphogypsum (PG) is a calcium sulfate-rich industrial by-product. Its large production volume and limited utilization have resulted in extensive stacking, which occupies land and places substantial pressure on the ecological environment and sustainable development [10]. This problem is particularly pronounced in Guizhou, China, where the PG utilization rate has remained below 40% since 2015 [11]. PG management also faces challenges associated with fluoride leaching (1-3 wt%) and contamination of adjacent aquifers [12], radioactive hazards exceeding safety thresholds for building materials by 2.3 times [13], and substantial land occupation for storage [14]. These constraints create an urgent need for effective PG disposal technologies and large-scale engineering applications. Using PG as an RBB material for coal mine GSER represents one potential route for such utilization.

Accordingly, the engineering conditions of the 11912 working face in a coal mine in Guizhou were investigated in detail and comprehensive experimental tests were performed. Following the principle of solid-waste resource utilization through "local sourcing, cost reduction, and efficiency improvement," this study evaluates local PG as an RBB material for coal mine GSER, with particular emphasis on the reasonable RBB width and associated economic benefits. The results are intended to

64 provide theoretical guidance and a case reference for the industrial application of PG.

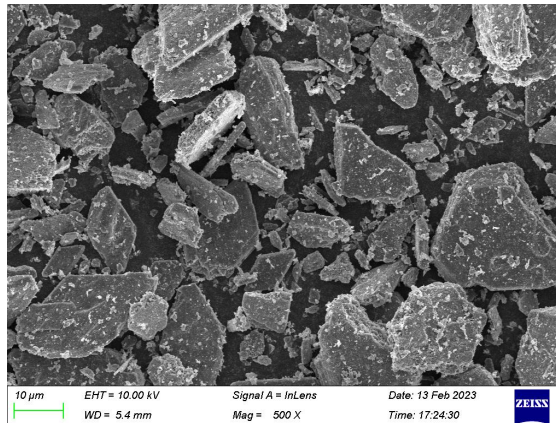
65 2. Raw materials and performance testing

66 2.1 Overview of raw materials

67 Following the basic principle of "local sourcing, cost reduction, and efficiency improvement," the
68 PG used in this study was obtained from Guizhou phosphate green environmental protection industry
69 company limited. PG calcined at 170°C was selected as the cementitious raw material for the
70 preliminary experimental analysis. The material consisted mainly of flaky hemihydrate calcium sulfate
71 crystals ($\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$), with particle sizes primarily ranging from 460 to 820 μm . The PG raw
72 material is shown in **Figure 1**.



73
74 (a) Macro morphology



75
76 (b) Microscopic morphology (SEM image)

2.2 Property testing

(1) Sample mix proportions

The specimen mix proportions are summarized in **Table 1**. The raw materials were used in the dry state and mixed at a low speed (140 r/min) for 30 min. Polycarboxylate superplasticizer (PCE), protein retarder (PR), and defoaming agent (DA) were incorporated at dosages of 0.2%, 0.06%, and 0.04% of the total mass, respectively, to prepare the phosphogypsum coal mine roadways support materials (PCMRSM). Specimens measuring 40 mm × 40 mm × 160 mm were molded at 25 ± 2 °C for 24 h, demolded, and cured under the same environmental conditions for 1 and 28 days before mechanical strength testing.

Table 1. Mixing proportions of PCMRSM specimens

Sample NO.	Main material and additives (wt %)					water-binder ratio	Initial fluidity (mm)
	PG	PCE	NaOH	PR	DA		
N0 (Reference)	99.36	0	0	0.6	0.04	0.42	50
N1	99.26	0.1	-	0.6	0.04	0.42	51
N2	99.16	0.2	-	0.6	0.04	0.42	58
N3	98.96	0.4	-	0.6	0.04	0.42	75
N4	98.56	0.8	-	0.6	0.04	0.42	85
N5	97.76	1.6	-	0.6	0.04	0.42	148
N6	99.26	-	0.1	0.6	0.04	0.42	50
N7	99.06	-	0.3	0.6	0.04	0.42	50
N8	98.76	-	0.6	0.6	0.04	0.42	50
N9	99.16	0.1	0.1	0.6	0.04	0.42	118
N10	98.96	0.1	0.3	0.6	0.04	0.42	134
N11	98.66	0.1	0.6	0.6	0.04	0.42	140
N12	99.06	0.2	0.1	0.6	0.04	0.42	138
N13	98.86	0.2	0.3	0.6	0.04	0.42	175
N14	98.56	0.2	0.6	0.6	0.04	0.42	158

(2) Flowability

Flowability is a key performance criterion for PCMRSM used in GSER. As shown in **Table 1**, NaOH alone did not improve the initial flowability, while low PCE contents (0.1-0.8 wt%) also

produced only limited improvement. Increasing the PCE content to 1.6 wt% markedly improved the initial fluidity of PCMRSM. However, at a market price of approximately 17,000 RMB/ton, such a high PCE dosage would substantially increase material costs and reduce the market competitiveness of PCMRSM as a building material. The combined addition of alkali and PCE was more effective in improving initial flowability. Through the synergistic effect of low contents of alkali and PCE, high flowability (> 140 mm) could be achieved while maintaining both technical feasibility and economic viability.

For the 30 min test, flowability before and after NaOH addition was compared at a fixed PCE content of 0.2 wt%. PCE alone did not provide sufficient flowability retention after 30 min, whereas the combined addition of alkali and PCE significantly improved fluidity and enabled PCMRSM to meet the standard requirements. Although increasing the water-binder ratio generally improves mortar flowability, even a slight change in this ratio may substantially affect subsequent mechanical properties. Tests at different water-binder ratios showed that high flowability could still be maintained at a lower water-binder ratio when alkali and PCE were used together, providing the potential to improve the mechanical and water resistance properties of PCMRSM. These results emphasize the importance of rationally selecting the type and content of alkali and PCE when designing PCMRSM with improved performance[15,16].

(3) Setting time

Setting time directly affects the construction performance and subsequent strength development of PCMRSM. **Figure 2** shows the effects of alkalis on the initial and final setting times. Alkali addition produced a marked change in setting behavior. With increasing NaOH content, both the initial and final setting times first increased and then decreased. At 0.15 wt% NaOH, the initial and final setting times

reached their maximum values of 139 min and 171 min, respectively. These results further confirm the pronounced effect of NaOH on the setting behavior of PCMRSM when combined with PCE.

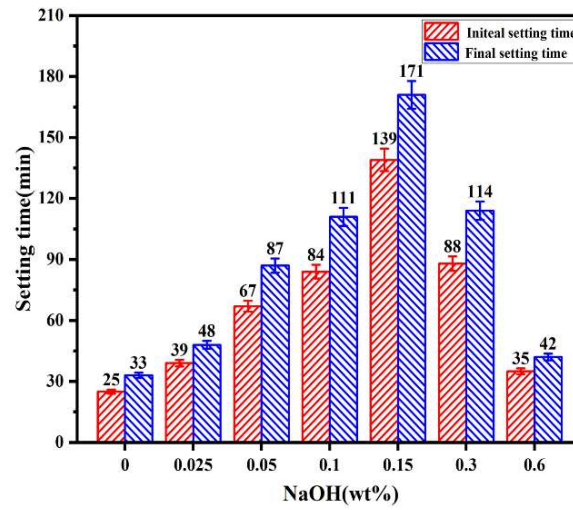


Figure 2 Setting times of the as-prepared specimens

(4) Compressive and flexural strength

Compressive and flexural strength tests were performed on PCMRSM specimens ($40 \times 40 \times 160$ mm) using a fully automatic testing machine (JYE-300B, China) in accordance with the Chinese standard (GB/T 9776-2022) [17]. The loading speed for the flexural strength test was 0.05 ± 0.01 kN/s. After flexural testing, the two resulting half mortar specimens were subjected to compressive strength testing at a loading rate of 2.4 ± 0.2 kN/s.

Figure 3 summarizes the compressive and flexural strengths of PCMRSM under alkaline conditions. In contrast to alkali activated materials, alkaline conditions did not improve the compressive strength of PCMRSM [18]. Instead, compressive strength decreased continuously as the NaOH content increased. At 0.6 wt% NaOH, the 28-day compressive strength was only 12.5 MPa, 44.45% lower than that of the control sample. The flexural strength initially increased and then decreased with increasing NaOH content, but the improvement was not significant.

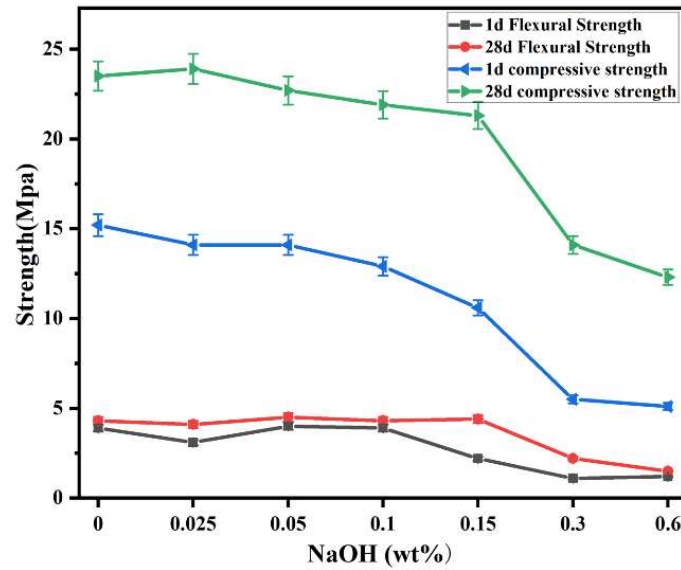


Figure 3 Mechanical properties of the as-prepared specimens

Overall, the strength, fluidity, and setting time of PCMRSM satisfied the specification requirements for GSER filling materials [19]. A low-alkali environment combined with PCE also favored higher PCMRSM strength and was therefore more suitable for its application in GSER.

3. Engineering overview and GSER mechanical model

3.1 Engineering geological conditions

The 11912 working face of a coal mine in Guizhou is a subsequent working face excavated along the goaf of the 11908 working face. The face has a strike length of 1200 m and an average coal seam dip angle of 6.5°. The mined seam is No. 19 coal in the middle section of the Permian Longtan Formation, with a mining height of 4.15 m, and is extracted using fully mechanized mining technology. The average burial depth of the working face is -520 m. **Table 2** summarizes the lithological characteristics of the roof and floor strata.

Table 2 Lithological characteristics of the roof and floor of the working face

No.	Coal and rock stratum	Thickness (m)	Characteristics
1	Siltstone	14.37	Light gray, thin to medium-thick bedded, with horizontal bedding and flaser bedding, containing plant fossil debris fragments.
2	Silty	6.86	Dark gray, thin-bedded, with horizontal bedding and chain bedding,

	mudstone		containing plant debris fragments, with granular pyrite.
3	Argillaceous limestone	0.86	Gray, thin to medium-bedded, cryptocrystalline texture, containing animal fossils, with massive pyrite.
4	No. 19 Coal (Roadway)	4.15	Black, columnar and massive, vitreous luster, step-like fracture, banded structure, containing granular pyrite, semi-bright type. Partings are gray-black mudstone, containing plant root fossils, nodular, simple structure, relatively seam.
5	Mudstone	2.67	Gray-black, nodular, containing plant root fossils, with granular and massive pyrite, containing vitrain bands.
6	Silty mudstone	5.02	Same as No. 2.
7	Mudstone	3.64	Same as No. 5.
8	Fine sandstone	15.47	Gray, thick-bedded, with wavy and flaser bedding, containing plant fossil debris fragments, intercalated with dark gray silty mudstone thin layers, calcareous cementation.

As shown in **Figure 4**, the 11908 working face is a GSER working face. After mining is completed, an artificial filling wall is retained along the goaf to form the retained entry. This entry subsequently serves as the mining gateway for the 11912 working face.

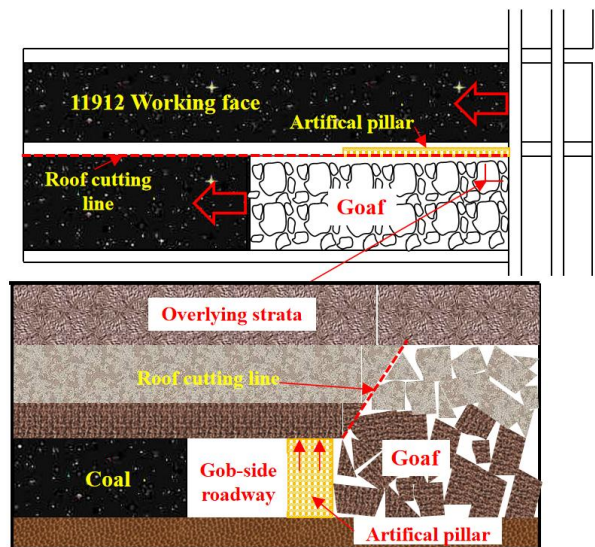


Figure 4 Schematic diagram of GSER

3.2 Mechanical model of GSER

GSER can generally be classified into three forms according to the width of the retained coal pillar: wide coal pillar GSER, narrow coal pillar GSER, and no-pillar GSER (full along-god roadway excavation) [20], as illustrated in **Figure 5**.

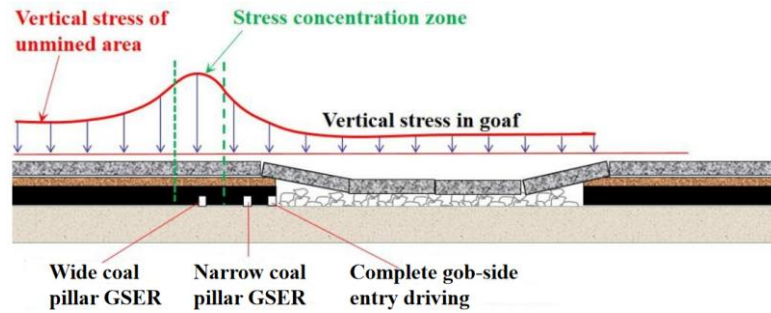


Figure 5 Three forms of GSER

(1) Wide coal pillar GSER: A large-width coal pillar is retained on the goaf side to ensure the safety of the coal mining working face. Although this configuration provides support, it causes substantial coal resource loss and a low recovery rate. In addition, the retained entry is located within the peak stress zone, where high stress levels can produce large deformation and increase subsequent maintenance costs. This form should therefore be avoided whenever conditions permit.

(2) No-pillar GSER: Entries are driven along the edge of the goaf without retaining a coal pillar. Practical applications of complete gob-side entry driving in China's mining engineering remain extremely limited, with only a small number of roadways reported publicly. The method offers advantages including resource saving, rapid entry formation, and minimum ground stress during driving, but it also faces substantial difficulties such as water hazards, gas outbursts, and spontaneous combustion of residual coal in adjacent goaf areas. These constraints limit its application [21].

(3) Narrow coal pillar GSER: A relatively small-width coal pillar is retained on the goaf side. This configuration balances coal recovery with working face safety and has long been the most widely used GSER mode in China's coal mining industry.

Continued advances in support theory, construction technology, and materials have enabled the use of paste concrete, high-water materials, metal props, wood cribs, gangue, and concrete to construct artificial roadside walls that replace the supporting role of coal pillars. These measures can further increase the coal recovery rate and have made GSER an important approach to pillarless mining. Roof

cutting GSER is one commonly used configuration, and its mechanical model is described below.

After roof cutting and pressure relief in the gateway of the 11912 working face, the roof fractures on the goaf side. Under the combined effects of ground stress and mining disturbance, the main roof fractures to form key block B , which rotates and sinks toward the goaf. Supported jointly by the roadway support structure, the roadside artificial filling body, and the loose rock mass in the goaf, key block B forms a stable hinged structure together with key block A on the solid coal side and key block C on the goaf side, as shown in **Figure 6**.

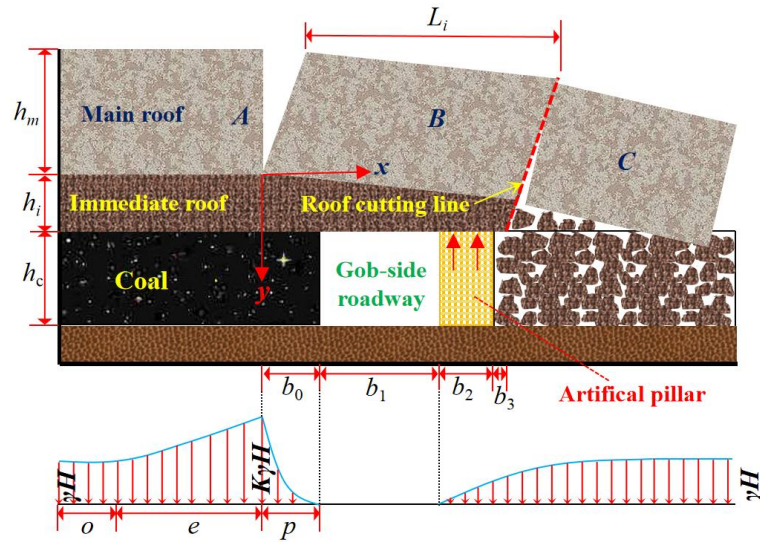


Figure 6 Mechanical model of GSER and vertical stress distribution

Under the influence of mining activities, the lower section coal body develops three deformation zones from the coal rib toward the deeper coal, as shown in **Figure 6**: the plastic failure zone (zone p), the elastic zone (zone e), and the original rock stress zone (zone o). Zone p is directly affected by mining activities in the upper section and is characterized by severe deformation, fragmentation, and low coal strength. Zone e is less affected and retains better coal integrity, whereas zone o is almost unaffected and remains stable under the original rock stress. Previous research [20] indicates that the stress distribution in these zones is approximately that shown in **Figure 6**.

As shown in **Figure 6**, the peak stress in the lower section coal body occurs at $x = b_0$,

corresponding to the junction between the elastic and plastic zones. The limit equilibrium equation at this location can be expressed as

$$\sigma_y|_{x=b_0} = k\gamma H; \quad \sigma_x|_{x=b_0} = \lambda\sigma_y|_{x=b_0} = \lambda k\gamma H \quad (1)$$

where: σ_x and σ_y are the horizontal and vertical stresses, respectively; $\lambda = 0.45$ is the lateral pressure coefficient; $k = 2$ is the stress concentration coefficient; $\gamma = 26 \text{ kN/m}^3$ is the unit weight of the overburden; and $H = 520 \text{ m}$ is the burial depth of the roadway.

A stress element is selected within zone p at the left coal rib of the roadway in Figure 6, and the corresponding mechanical model is shown in Figure 7.

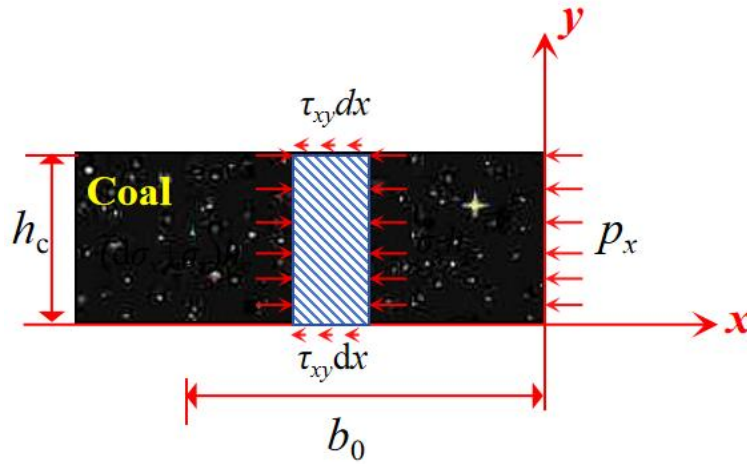


Figure 7 Stress element in zone p of the coal rib

Combining the limit equilibrium equation with the Mohr-Coulomb strength criterion gives the following expression for the plastic failure zone (zone p) through physical and mechanical analysis [22]

$$b_0 = \frac{\lambda h_c}{2 \tan \varphi_0} \ln \frac{k\gamma H + c_0 / \tan \varphi_0}{c_0 / \tan \varphi_0 + p_x / \lambda} \quad (2)$$

where: $p_x = 0 \text{ MPa}$ is the support resistance of the roadway rib; $h_c = 4.15 \text{ m}$ is the mining thickness of the coal seam in the working face; and $\varphi_0 = 38.21^\circ$ and $c_0 = 2.12 \text{ MPa}$ are the internal friction angle and cohesion between the coal seam and the roof/floor, respectively.

Substituting these parameters into Equation (2) yields $b_0 = 2.85 \text{ m}$.

4. Determination of RBB strength and analysis of influencing factors

The artificial filling wall for GSER in the 11912 working face is cast on-site using PCMRSM. Filling material strength directly affects retained entry stability and mining safety. Because the available construction space in coal mine roadways is extremely limited, increasing filling material strength can reduce the required RBB width and thereby increase the coal recovery rate. Quantifying the relationship between RBB strength and width, together with the sensitivity of the relevant influencing factors, is therefore necessary for determining the required RBB strength.

4.1 Calculation theory for RBB strength in GSER

Numerous methods and theories have been proposed for calculating RBB strength in GSER, including the estimation method, separated rock block method, inclined rock beam method, superimposed layer plate method, arc triangular block stability method, block equilibrium method, structural coordinated bearing mechanical model, and elastic thin plate roof movement mechanical model [23]. In practice, however, many of these approaches are constrained by cumbersome calculations, extensive assumptions, or parameters that cannot be readily determined [24]. The present analysis therefore focuses on two widely applied classical methods, the estimation method and the separated rock block method, and compares their calculation results.

(1) Estimation method

The estimation method originates from theoretical studies of stope ground pressure and has been incorporated into some "Mining Engineering" textbooks in China. It is a relatively well-recognized theoretical approach for calculating RBB strength in GSER. The method assumes that the maximum load carried by the RBB equals the weight of the immediate roof above the wall, roadway, and weak zone (plastic zone) of the coal rib. Roof pressure is represented by the weight of the overlying rock

mass with $n = (4\sim 8)$ times the mining height [25]. Accordingly, the roof pressure can be expressed as

$$Q = (b_0 + b_1 + b_2 + b_3) n \gamma h_c \quad (3)$$

where: $b_1 = 4.5$ m is the width of GSER; b_2 is the RBB width to be determined; and $b_3 = 1.0$ m is the overhanging width of the cantilever beam.

Accordingly, the relationship between RBB width and strength obtained using the estimation method is as follows

$$\sigma_{1d} > \frac{(b_0 + b_1 + b_2 + b_3) n \gamma h_c}{b_2} \quad (4)$$

where: σ_{1d} is the compressive strength of the filling body material at 1 d, in MPa.

(2) Separated rock block method

The separated rock block method was first proposed by British scholar Whitaker and has been incorporated into China's "coal mine support handbook" [26]. It provides a relatively practical theoretical approach for calculating RBB strength, and its mechanical model is shown in **Figure 8**.

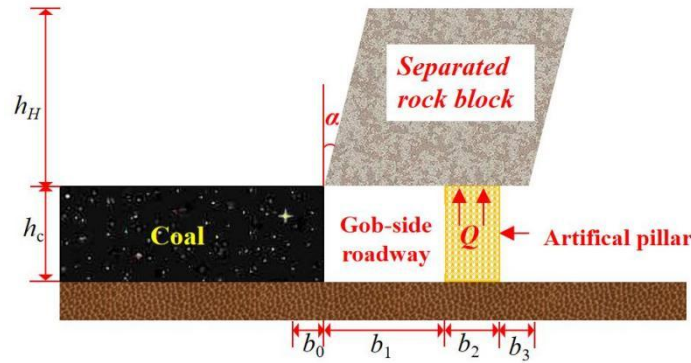


Figure 8 Mechanical model of separated rock block method

The theoretical basis of this method is as follows. After the working face is mined, rock masses within a certain range above the roadway form separated rock blocks, and the support body carries the weight of the separated blocks above the gob-side roadway and the support body. The roadside support lies between the high ground pressure zone of the unmined coal body and the caved gangue in the goaf, thereby forming a pressure relief zone. The goaf provides a main free face on one side of the rock

block. Because the rock blocks are layered, bed separation may occur at a certain height (h_H), causing the blocks to fracture at an angle α to the coal wall, enter a completely free state, and act as a load on the roadside support. Generally, $h_H = 4hc$ and $\alpha = 26^\circ$. **Figure 8** illustrates the calculation principle.

Using this method, the load per unit length of the filling body is calculated as [27]

$$q = \frac{8h_c \tan \alpha + 2(b_1 + b_2 + b_3)}{b_2} \times \frac{h_c(b_1 + b_2 + b_3)\gamma \cos \theta}{b_1 + 0.5b_2} \quad (5)$$

where: $\theta = 6.5^\circ$ is the coal seam dip angle, and $\alpha = 26^\circ$ is the immediate roof caving angle.

Equation (5) yields the following relationship between filling body width and strength

$$\sigma_{ld} > q = \frac{8h_c \tan \alpha + 2(b_1 + b_2 + b_3)}{b_2} \times \frac{h_c(b_1 + b_2 + b_3)\gamma \cos \theta}{b_1 + 0.5b_2} \quad (6)$$

(3) Width design of RBB

For the GSER engineering of the 11912 working face, **Equations (4) and (6)** were used to determine the relationship between RBB width and strength using the estimation method and the separated rock block method, respectively. The resulting curves are shown in **Figure 9**.

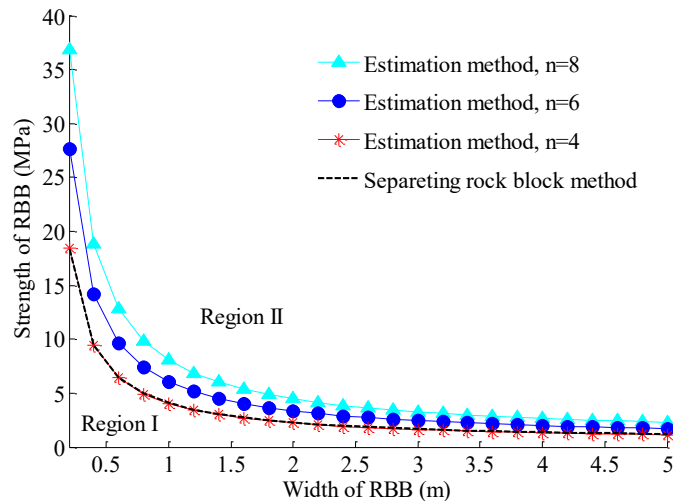


Figure 9 Comparison of RBB width and strength

Region I below the curves represents the failure and instability zone, whereas Region II above the curves represents the safety and stability zone. As shown in **Figure 9**, when RBB width is below 1.0 m,

the required RBB strength decreases rapidly as width increases. Once the width exceeds 2.5 m, further increases produce only a small reduction in the required RBB strength. Considering filling cost and field engineering experience from surrounding mines, an RBB width of 1.0 - 2.5 m is appropriate for the GSER engineering of the 11912 working face.

For the GSER engineering of the 11912 working face, the result from the separated rock block method corresponds to a special case of the estimation method at $n = 4$. The estimation method gives more conservative results. Accordingly, the subsequent analysis of the factors influencing RBB strength and their sensitivities is based on the estimation method to maintain a conservative safety margin.

4.2 Analysis of factors influencing RBB strength

Substituting the expression for the fracture position b_0 of key block B from **Equation (2)** into **Equation (4)** gives the following relationship between the influencing factors and filling material strength

$$\sigma_{ld} > \frac{\left(\frac{\lambda h_c}{2 \tan \varphi_0} \ln \frac{k\gamma H + c_0 / \tan \varphi_0}{c_0 / \tan \varphi_0 + p_x / \lambda} + b_1 + b_2 + b_3 \right) n \gamma h_c}{b_2} \quad (7)$$

Equation (7) shows that filling material strength is influenced not only by RBB width b_2 but also by the lateral pressure coefficient λ , coal seam height h_c , cohesion c_0 , internal friction angle φ_0 , overburden unit weight γ , roadway burial depth H , roadway width b_1 , roadside support p_x , cantilever beam overhanging width b_3 , and roof pressure multiple n . Taking the grouting material strength σ_{ld} as the characteristic function and using the working condition data ($\lambda = 0.45$, $k = 2$, $H = 520$ m, $\gamma = 26$ kN/m³, $h_c = 4.15$ m, $c_0 = 2.12$ MPa, $\varphi_0 = 38.21^\circ$, $b_1 = 4.5$ m, $b_2 = 2.0$ m, $b_3 = 1.0$ m, $n = 8$, $p_x = 0$ MPa) as the baseline, the variation curves of σ_{ld} with each factor were calculated, as shown in **Figure 10**.

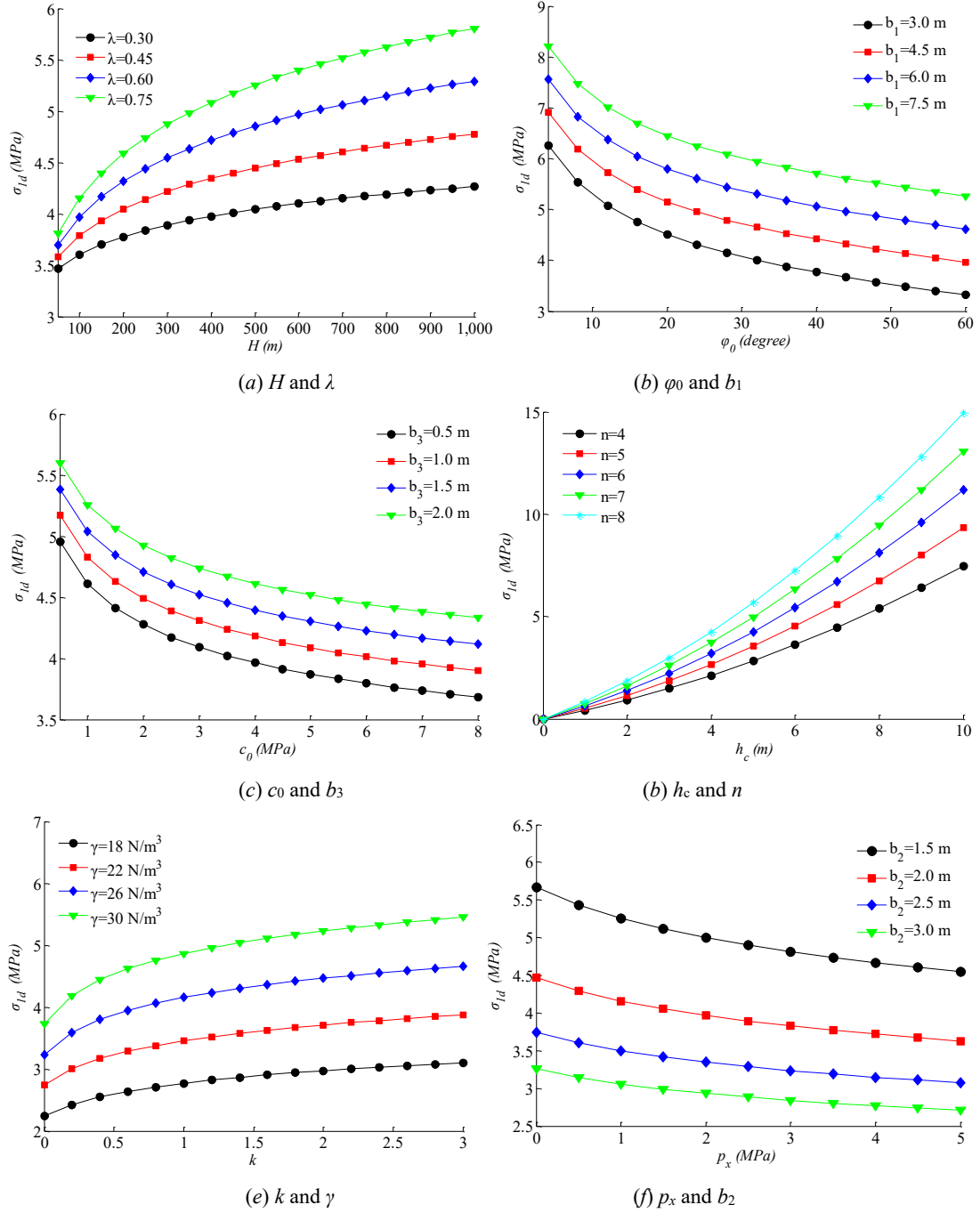


Figure 10 Variation in filling wall strength with each factor

According to **Equation (7)**, σ_{ld} increases linearly with λ , b_1 , b_3 , and n , increases nonlinearly with H , h_c , and k , and decreases nonlinearly with b_2 , c_0 , φ_0 , and p_x . The same trends are evident in **Figure 10**. Overall, σ_{ld} is governed by three groups of factors: ground pressure, rock properties, and roadway strata dimensions.

To quantify the sensitivity of σ_{ld} to each factor and distinguish the primary and secondary

influences, the sensitivity coefficient for each factor was calculated using the following equation [28].

$$A(x_s^*) = \left| \frac{d\sigma_c(x_s)}{dx_s} \right|_{x_s=x_s^*} \frac{x_s^*}{\sigma_c(x_s^*)}, \quad s = 1, 2, \dots, n \quad (8)$$

where: $A(x_s^*)$ is the sensitivity coefficient when factor x_s takes the reference value x_s^* ; $\sigma_{1d}(x_s)$ is the characteristic function containing factor x_s ; and $\sigma_{1d}(x_s^*)$ is the characteristic value when factor x_s takes the reference value x_s^* . $A(x_s^*)$ is dimensionless, and a larger value indicates greater sensitivity of the characteristic function $\sigma_{1d}(x_s)$ to factor x_s .

Using **Equation (8)**, the sensitivity coefficients of the twelve factors λ , k , H , γ , h_c , c_0 , φ_0 , b_1 , b_2 , b_3 , n , and p_x to the grouting material strength σ_{1d} were calculated as 0.2753, 0.1042, 0.1042, 1.1042, 1.2753, 0.1042, 0.3519, 0.4348, 0.8067, 0.0966, 1.0000, and 0.000, respectively. Based on the magnitude of $A(x_s^*)$, the sensitivities of these factors to σ_{1d} decrease in the following order: $h_c > \gamma > n > b_2 > b_1 > \varphi_0 > \lambda > k = H = c_0 > b_3 > p_x$.

Among the evaluated factors, σ_{1d} is most strongly affected by coal seam thickness h_c , and **Figure 10(b)** shows that σ_{1d} increases with h_c at an accelerating rate. The next strongest influences are γ and n , for which σ_{1d} increases at an approximately constant rate, as shown in **Figures 10(b)** and **10(e)**. The effects of b_2 , b_1 , φ_0 , and λ are lower, and the rate of change in σ_{1d} with these factors decreases rapidly. By comparison, c_0 , H , k , and b_3 exert smaller effects. The influence of p_x is minimal and can almost be neglected. Therefore, if conditions permit, the last five factors can be treated as secondary factors.

5. Simulation analysis of reasonable RBB width

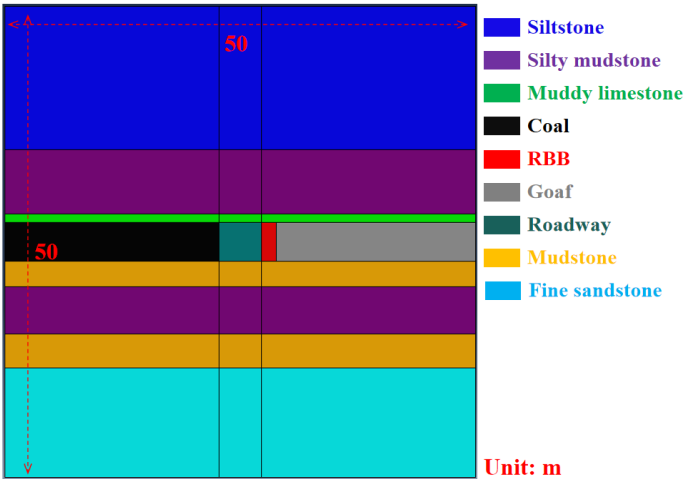
5.1 Numerical simulation

Based on the material test results, phosphogypsum was used as the main RBB material, with PCE,

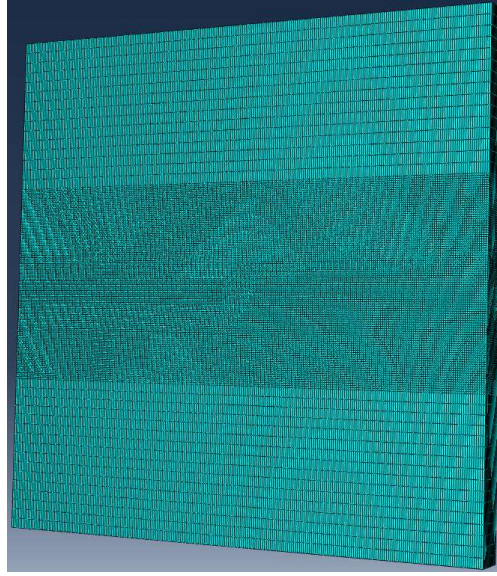
PR, and dDA added at dosages of 0.2%, 0.06%, and 0.04% of the total mass, respectively. The water reducer concentration was adjusted to 0.1%~0.5%, and the water content was set to 42% of the solid mixture to meet the basic requirements of the mining filling method.

(1) Model establishment

Based on the gob-side entry conditions of the 11912 working face, a three-dimensional mechanical model measuring 50 m × 50 m × 3 m (length × width × thickness) was established in ABAQUS, with the retained entry positioned at the center of the model. The mesh comprised 508,500 8-node linear brick elements, with a dense distribution internally and a sparse distribution externally, as shown in **Figure 11**.



(a) Model overview



(b) Model mesh division

Figure 11 Numerical model

A uniformly distributed vertical load of 12.26 MPa was applied to the top boundary to represent the load imposed by the overlying strata. Model self-weight was included by setting the gravitational acceleration to $g = 9.81 \text{ N/kg}$, and lateral pressure was represented using the lateral pressure coefficient $\lambda = 0.45$. The Z-direction displacement of the bottom boundary was fixed at 0, as were the X-direction displacements of the left and right boundaries and the Y-direction displacements of the front and rear boundaries.

During the numerical simulations, RBB width was varied from 0.8 m to 3.6 m in increments of 0.2 m to evaluate changes in surrounding rock stress and deformation and thereby determine the filling body thickness more precisely. Rock mass failure was governed by the Mohr-Coulomb criterion. The basic physical and mechanical properties of the coal and rock masses were taken from measured geological parameters, while the goaf parameters were assigned according to the mechanical properties of loess [29], as listed in **Table 3**.

Table 3 Physical and mechanical parameters of coal and rock mass

Rock stratum	Unit weight (kN/m^3)	Elastic modulus (GPa)	Poisson's ratio	Cohesion (MPa)	Internal friction angle (degree)
Siltstone	2685	11.52	0.24	8.32	31.23

Silty mudstone	2513	3.48	0.27	6.48	29.56
Muddy limestone	2475	2.88	0.30	5.45	32.10
No. 19 coal	1400	1.21	0.29	1.14	18.63
RBB	2287	1.65	0.34	2.53	21.30
Goaf	2000	0.2	0.40	0.009	15
Mudstone	2461	1.98	0.33	3.61	27.79
Fine sandstone	2786	13.48	0.21	14.18	36.10

(2) Results analysis

Figure 12 presents the displacement distribution of the surrounding rock in the retained entry for different RBB widths.

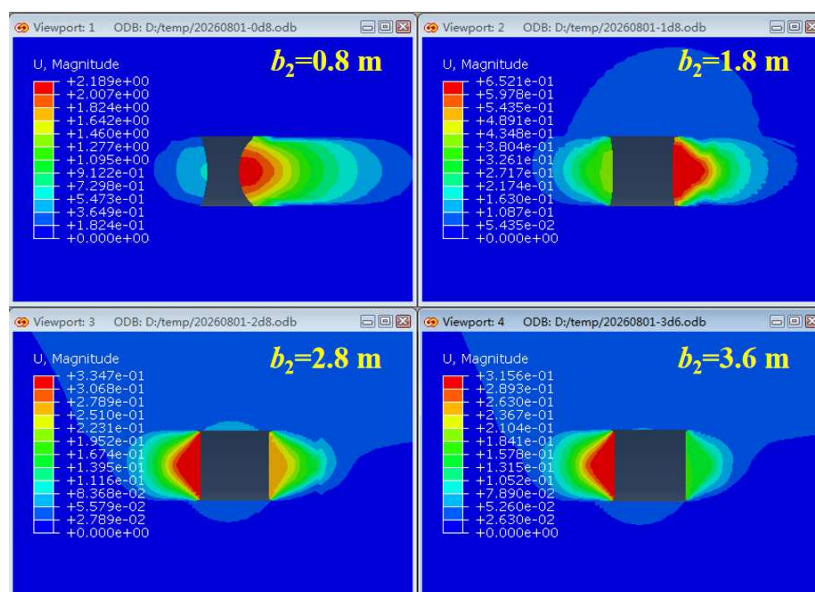


Figure 12 Variation in surrounding rock displacement in GSER with RBB width

Figure 12 indicates that surrounding rock deformation in GSER is dominated by convergence of the two ribs, while roof and floor deformation remains relatively small. As RBB width increases, convergence of the RBB side rib decreases progressively and approaches a stable level. At the same time, the position of maximum displacement shifts from the RBB side rib toward the solid coal side rib, indicating progressive stabilization of the RBB side rib. On this basis, the reasonable RBB width is estimated to range from 1.8 to 2.8 m.

To examine the effect of RBB width on retained entry deformation in greater detail, the midpoints of the roof, RBB side rib, and solid coal side rib were selected as displacement monitoring points.

Figure 13 shows the resulting deformation of the retained entry under the different RBB width conditions.

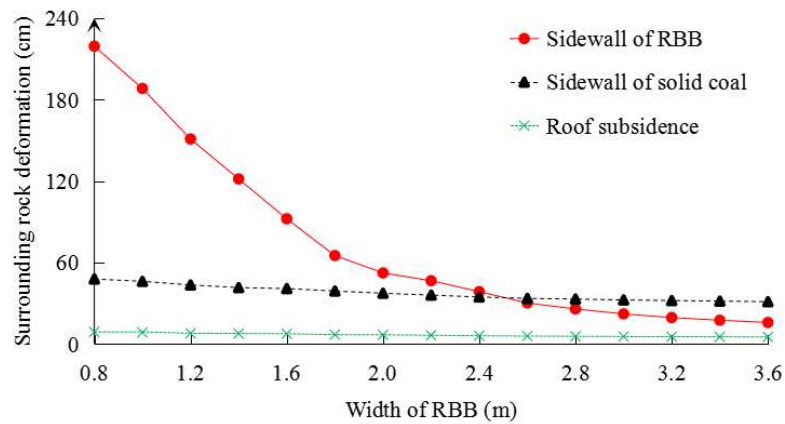


Figure 13 Variation in monitoring point displacement in GSER with RBB width

As shown in **Figure 13**, deformation of the retained entry is dominated by convergence of the RBB side rib. Deformation of the roof and floor and of the surrounding rock on the solid coal side is comparatively small and is not significantly affected by RBB width. With increasing filling body width, convergence of the RBB side rib can be divided into three stages:

1) Rapid deformation decrease stage. At RBB widths of 0.8 – 2.0 m, convergence of the RBB side rib decreases rapidly as the width increases. Increasing the RBB width from 0.8 m to 2.0 m reduces convergence from 219.38 cm to 52.43 cm, corresponding to an overall decrease of 76.10%.

2) Slight deformation decrease stage. At RBB widths of 2.0 – 2.6 m, convergence of the RBB side rib decreases more gradually with increasing width. As the RBB width increases from 2.0 m to 2.6 m, convergence decreases from 52.43 cm to 30.33 cm, representing a decrease of 10.07% compared with an RBB width of 0.8 m.

3) Basically stable deformation stage. When RBB width exceeds 2.6 m, convergence of the RBB side rib continues to decrease as the width increases, but the magnitude is relatively small and lower than that of the solid coal side rib. This indicates that the surrounding rock of the retained entry has

become basically stable.

Accordingly, the variation in surrounding rock deformation with RBB width indicates that a reasonable RBB width is approximately 2.0 m.

Figure 14 shows the distribution of plastic zones in the surrounding rock of the retained entry under different RBB width conditions.

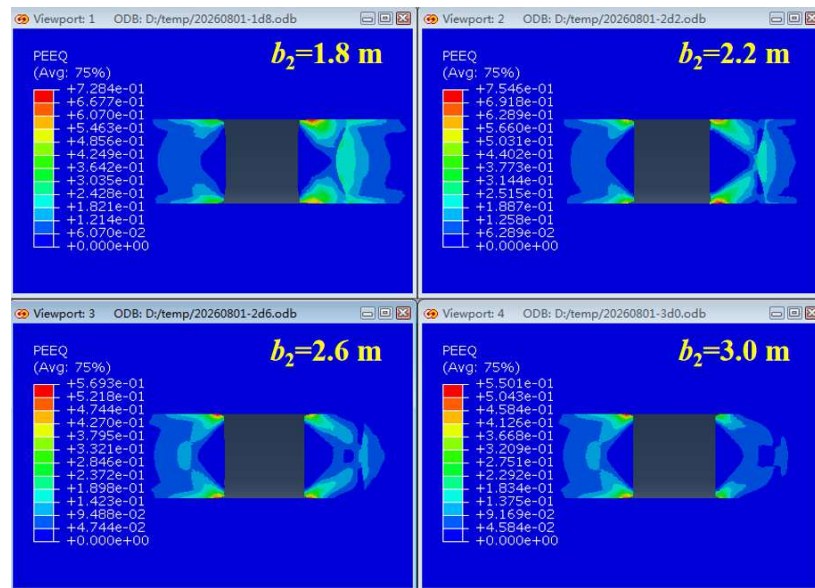


Figure 14 Variation in plastic zones in the surrounding rock of GSER with RBB width

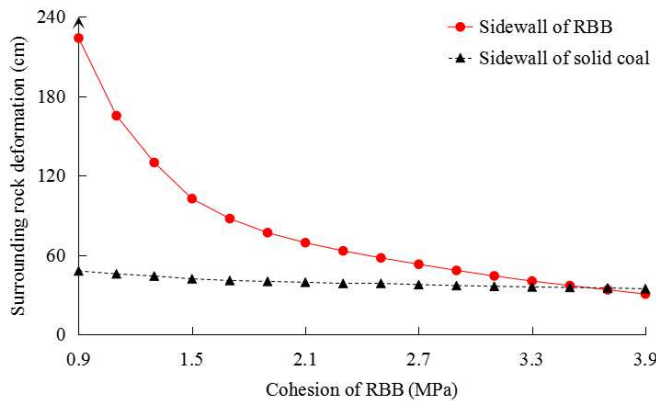
As shown in **Figure 14**, at an RBB width of 1.8 m, the relatively small width and insufficient bearing capacity leave the RBB interior in a plastic failure state under extrusion by the roof strata. Increasing the width to 2.2 m improves the bearing capacity and reduces internal plastic failure, although most of the RBB remains in a plastic failure state. At 2.6 m, the bearing capacity is basically sufficient to withstand extrusion by the overlying rock mass, and the central region of the RBB enters an elastic deformation state. Further increasing the width to 3.0 m produces only a slight expansion of the elastic deformation region despite the continued increase in bearing capacity. Based on the evolution of the plastic zones, a reasonable RBB width of 2.2-2.6 m is obtained, representing a relatively conservative range.

Overall, an RBB width of 2.0 m can basically satisfy the on-site production safety requirements.

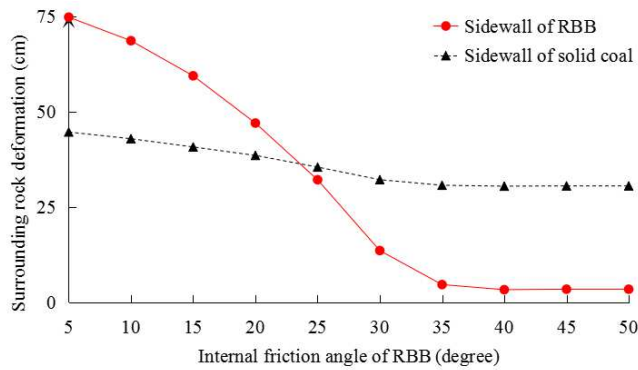
Although a further increase in width can reduce retained entry deformation and the extent of the plastic zone, the associated material cost and the limited construction space must also be considered. On this basis, the reasonable RBB width is determined to be 2.0 m.

5.2 Sensitivity analysis of RBB material parameters

Cohesion c and internal friction angle φ are key parameters characterizing the strength of geotechnical materials and are also intrinsic factors governing the deformation and mechanical distribution of roadway surrounding rock. For the above model with an RBB width of 2.0 m, Figure 15 presents the calculated variation in retained entry surrounding rock displacement with RBB material cohesion and internal friction angle.



(a) Influence of c



(b) Influence of φ

Figure 15 Sensitivity analysis of RBB material parameters

Figure 15 shows that increasing the cohesion and internal friction angle of the RBB material can markedly reduce retained entry displacement, particularly when the strength parameters are relatively small ($c < 2.1$ MPa or $\varphi < 35^\circ$). At larger values ($c > 2.4$ MPa or $\varphi > 35^\circ$), further increases in cohesion or internal friction angle have almost no effect on surrounding rock displacement. The strength parameters of the PCMRSM proposed in this study ($c = 2.53$ MPa or $\varphi = 21.30^\circ$) are already sufficiently high. Although a further increase in φ can still reduce roadway deformation to some extent, the additional effect is limited.

6 Brief benefit analysis

Because RBBs are constructed within the extremely limited space of coal mine roadways, reducing RBB width can preserve more coal resources. The above test results indicate that alkali content has a significant effect on the strength of PGSLM. According to previous research, the 1-day compressive strength of PGSLM as a filling material ranges from 5.08 MPa to 15.25 MPa. Based on a conservative calculation using the estimation method ($n = 8$), the RBB widths required to ensure production safety are 1.71 m and 0.51 m, respectively. A brief economic benefit analysis is presented below.

The float coal volatile matter of the coal seam in the 11912 mining face ranges from 6.88% to 9.99%, and the maximum vitrain reflectance ranges from 2.82% to 3.29%. According to China's national standard for coal classification, "GB/5751 — 2009" [30], the coal in the mining face is classified as anthracite No. 3 (WY3), with an average density of 1.62 t/m^3 . As the required safe RBB width decreases from 1.71 m to 0.51 m with increasing strength, the additional amount of coal recoverable from the 11912 working face can be calculated as

$$C = 1200 \text{ m} \times 4.15 \text{ m} \times (1.71 - 0.51) \text{ m} \times 1.62 \text{ t/m}^3 = 9681.1 \text{ t} \quad (9)$$

These results indicate that using PGSLM as the RBB material for GSER in the 11912 mining face can yield relatively significant economic benefits.

7. Discussions

Laboratory testing established the fluidity, setting time, and strength characteristics of the phosphogypsum material and showed that, when combined with PCE in a low-alkali environment, PGSLM exhibits higher strength while meeting the fluidity and setting time requirements for gob-side entry retaining filling bodies. Theoretical analysis and numerical simulation were then used to relate material performance to RBB design and to evaluate the sensitivity of the principal influencing factors. Together, these results provide a basis for applying PCMRSM to artificial filling walls in the 11912 working face and for selecting an RBB width appropriate to the site conditions. However, the durability, ecological environmental protection characteristics, and groundwater pollution features of this material require further investigation before the rationality and feasibility of its broader use for underground roadway filling can be fully established. Combining phosphogypsum with on-site mining wastes such as tailings sand and coal gangue, supplemented with a certain amount of cement, may further improve filling body strength and offers another potential route for waste utilization.

More broadly, China has accumulated large quantities of industrial solid wastes such as phosphogypsum, while filling mining and roadway grouting reinforcement technologies have become increasingly mature. Incorporating such industrial solid wastes into cement-based materials for grouting reinforcement of fractured roadway surrounding rock can improve the overall strength of the surrounding rock while promoting the resource utilization of industrial solid wastes. This direction therefore warrants further investigation.

8. Conclusions

Based on the GSER engineering of the 11912 working face in a coal mine in Guizhou Province, this study combined strength testing, analytical calculations, sensitivity analysis of influencing factors, and a brief benefit analysis to evaluate RBB materials and determine a reasonable RBB width for GSER. The main conclusions are as follows.

(1) Comparative tests showed that PCMRSM attains higher strength in a low-alkali environment combined with PCE, while its fluidity and setting time satisfy the requirements for gob-side entry retaining filling bodies.

(2) For the GSER engineering of the 11912 working face, analytical calculations showed that the RBB width obtained using the separated rock block method corresponds to a special case of the estimation method at $n = 4$. The estimation method gives more conservative results and may therefore provide a safer and more reliable basis for engineering application.

(3) Sensitivity analysis showed that, for the GSER engineering of the 11912 working face, h_c , γ , and n are the main factors affecting RBB strength; b_2 , b_1 , φ_0 , and λ are secondary factors; and k , H , b_3 , c_0 , and p_x can be regarded as general factors. The sensitivities of the factors decrease in the following order: $h_c > \gamma > n > b_2 > b_1 > \varphi_0 > \lambda > k = H = c_0 > b_3 > p_x$.

(4) Numerical simulations characterized the variation in surrounding rock deformation in the GSER of the 11912 working face with RBB width and indicated a reasonable width of 2.0 m.

The laboratory tests and brief engineering benefit analysis further indicate that maintaining a low-alkali environment for the filling material favors higher PCMRSM strength, thereby increasing coal resource recovery and reducing construction costs.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Hailong Dong developed the research ideas, provided the research site, and designed the technical plan. Jingyu Ran supervised the research and proposed the research direction. Jianjun Jiao was responsible for report analysis and manuscript preparation. Junhui Zou, Rongjiang Zhou, and Zhengxin Zhang contributed to manuscript preparation.

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