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Preliminary Exploration of the Technology of Coal Reshaping and Replacement Mining of Abandoned Coal in Goafs

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Abstract: Recycling of coal resources left behind in goafs and the treatment and utilization of solid waste from mines are topical issues faced by the global coal mining industry at present. With the annual reduction of recoverable reserves of coal resources and the dependence on coal resources that are difficult to replace, the problems have become increasingly prominent, seriously limiting the development of coal resources and the implementation of environmental protection work. The mutual influence between the strength of filling materials and the size of loose coal in the CRRM process through numerical simulation experiments, laboratory rock mechanics experiments, and on-site large-scale similar simulation material experiments is explored. It is ultimately believed that selecting a filling material with a 20 cm particle size of loose coal and a 90% proportion of loose coal for 7 days can meet the requirements of the CRRM process, and this conclusion has been verified through on-site engineering scale experiments. The scientific problems faced by various links in the process of filling and replacing abandoned coal in goafs were analyzed, and improvement methods were further proposed; the technical system of filling and replacing abandoned coal was improved, and new directions for the efficient and safe recovery of abandoned coal resources worldwide in the future were developed.

Keywords: coal recycling; replacement mining; filling material

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Citation: Li, L.; Zhang, X.; Hu, B.; Lei, S. Preliminary Exploration of the Technology of Coal Reshaping and Replacement Mining of Abandoned Coal in Goafs. *Processes* **2023**, *11*, 2474. https://doi.org/10.3390/pr11082474

Academic Editors: Carlos Sierra Fernández, Feng Du, Aitao Zhou and Bo Li

Received: 18 July 2023
Revised: 8 August 2023
Accepted: 16 August 2023
Published: 17 August 2023

1. Introduction

Coal has long been one of the most abundant and widely distributed pillar energy sources on Earth, with the most convenient ease of use and downstream products [1]. By the end of 2022, the world's proven coal resources reserve was 1.07 trillion tons, of which the United States accounts for 23.2% [2], reaching 248.941 billion tons, and China accounts for 13.3% [3], reaching 207.886 billion tons [4]. Although major energy production and consumption entities around the world are constantly and vigorously adjusting their energy structure, the dependence of various countries on coal resources will be difficult to change for a considerable period in the future. Moreover, in the early stages of mining technology development, China, the United States, and European countries generally have mining processes such as room pillars and knife pillars that support the roof and overlying rock through leftover coal bodies [5]. Many high-quality coal resources still need secondary development [6].

The United States Geological Survey (USGS), together with the U.S. Bureau of Mines and the Energy Information Administration (EIA), jointly found that the mining output of coal only accounts for 50~60% of the proven reserves, while the average recovery rate of coal mines in China is 30~35% [7], the recoverable reserves of coal reserves in China reach 40 billion tons [8,9], and the burial depth is generally shallow. Current coal resource mining has entered the deep stage and is facing many complex environmental stress problems.

The secondary development of high-quality coal resources left behind in shallow buried areas is even more urgent, as shown in Figure 1.

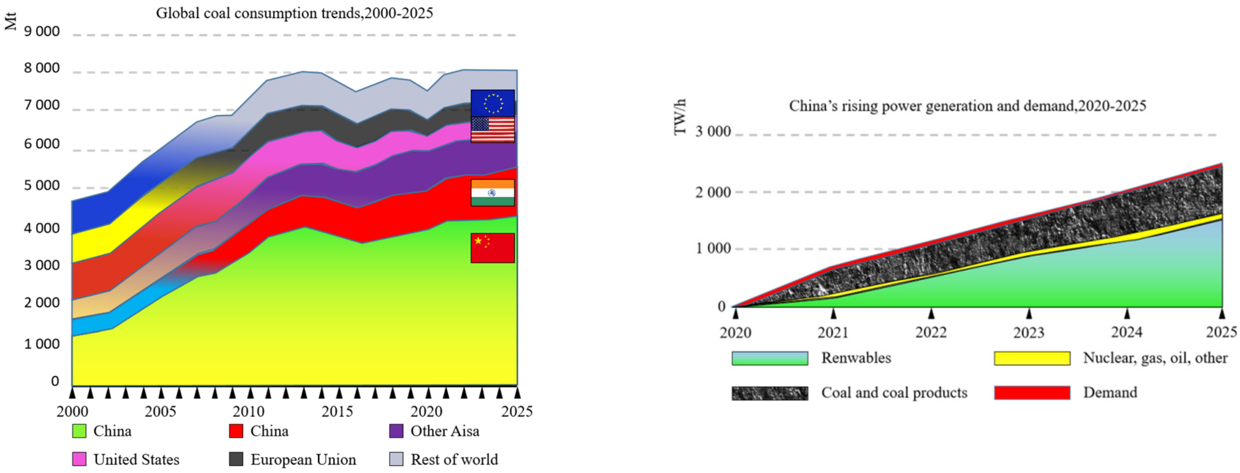


Figure 1. Global coal consumption trends (2000–2025) and China's energy supply and demand relationship (2020–2025). [Coal medium-term market report—Details—Trove.].

In recent years, experts and scholars around the world have also conducted a large amount of targeted research on the mining pressure theory and the technology of residual coal mining.

Stefaniak S and Twardowska I et al. [10] studied the range of rock disturbance during the process of residual coal remining and the reuse of secondary coal resources. They also studied the impact of acid (ARD) and neutral rock drainage (NRD) on the environment from two physical and chemical perspectives on the mining waste generated during coal mining.

Shimada H [11] et al. analysed and discussed the applicability of longwall mining faces in the large-scale recovery of residual coal and their industrial design methods through numerical simulation, focusing on the stability of coal walls and the improvement of the recovery rate during the stage of residual coal remining. They conducted in-depth research on the slope and mining boundary stability issues that occurred during the recovery of residual coal resources and comprehensively considered the coal resource recovery rate. Reasonable support design parameters were provided under safe and environmental conditions.

Scientific research on the theory of residual coal resource extraction by Chinese experts and scholar teams has also made significant progress.

Feng, GR, Zhang, RJ [12,13] et al. carried out an analysis on the structural stability of the surrounding rock of the stope when the full seam residual coal is mined by long-wall working face filling or full caving method by means of numerical simulation, field measurement and physical similar simulation experiments and put forwards the idea and technology of constructing a "filling body direct roof" structure through gangue filling to control the movement of rock strata and protect the longwall working face of residual coal recovery.

Xv, JC et al. [14] proposed a calculation method for the limit parameters of coal spontaneous combustion in residual coal mining areas based on heat generation intensity, oxygen consumption rate, and energy conservation principle of loose coal determined by coal spontaneous combustion experiments. This provides an effective theoretical basis for the prevention and control of concealed dangers of spontaneous coal combustion during the residual coal remining stage.

Cheng, WM et al. [15] studied the coupling mechanism of gas and residual coal spontaneous combustion in the goaf of a fully mechanized top coal caving face and further derived the multiparameter influence evolution law of residual coal spontaneous combustion and gas coupling disaster in the goaf through a multifield coupling 3D reconstruction method.

They improved the high-level drilling gas drainage and the injection of fireproof material technology in the goaf of residual coal, ensuring the gas limit requirements of the working face during the process of residual coal remining.

Regarding the application of rock pressure theory and filling materials in the filling mining process, Zhou, HQ et al. [16] proposed five paste material filling mining methods and verified their feasibility.

Zhang JX et al. [17] systematically studied the characteristics of mining pressure, key rock strata movement, and surface deformation in the application process of the gangue direct filling comprehensive mining method through experimental analysis and numerical simulation.

Bai, JB et al. [18] started from two main lines, stress control and surrounding rock reinforcement, and analysed the impact of advanced mining on the working face during high water material filling mining, the stability of the retained roadway surrounding rock, and the stress and deformation characteristics of the adjacent working face during the mining stage. They proposed a design method for key parameters of surrounding rock control in high-water material filling mining.

Feng and GM [19] proposed through a large number of laboratory experiments that A and B mixed ultrahigh water filling materials, with a 95% water volume ratio as the boundary between high and ultrahigh water materials. They successfully used ultrahigh water materials in coal mining sites to extract coal seams under buildings.

To fill and remine the remaining coal resources in the goaf, the mechanical support parameters of the filling material on the goaf roof were studied. For the preparation of inorganic high water materials using fly ash (CFA) and residual slag as raw materials, second-order and pseudo-first-order dynamic models were fitted to reduce the maintenance synthesis time [20–22].

For the process of recycling and utilizing residual coal resources, Wang, F., and Zhang, C team [23] used the Mark Bieniawski formula and numerical simulation to calculate the reasonable width of coal pillars and intelligent slope mining in the longwall working face. They analysed the stress state of the surrounding rock in the goaf of residual coal resources, achieving safe, efficient, and high recovery rates in the longwall working face mining of the goaf.

During the secondary mining process, under the action of mining stress, the continuous fracture and instability of the roof in the roof caving area (RCZ), as well as the evolution process of the safety and efficiency of mining residual coal resources [24], were simulated physically and analysed on-site. It was found that the rotation of the basic roof fracture towards the goaf in the RCZ area significantly increases the support pressure of the hydraulic support in the working face, and the sudden instability of the coal pillar also weakens its support effect on the basic roof. A mechanical model was established for the interaction between the surrounding rock and support in the goaf of residual coal remining, and the pregrouting solidification repair technology in the RCZ was studied to improve the bearing capacity of the coal pillar.

For mining areas after noncomplete caving mining activities, Prakash A et al. [25] systematically studied the effects of rainfall, secondary mining disturbances, and other behaviours on the surface subsidence effect of working faces. Mine entries close to residual bearing coal pillars (RBCPs) will suffer large deformation that may cause rock burst. To better understand the deformation mechanism and develop safe and practical guidelines for entry design, most studies focus on the absolute size of the stress field in and around the pillar. Kang J's team [26] proposed a formula for deriving the support pressure of residual coal pillar surrounding rock using the stress concentration coefficient (SCC), stress gradient (SG), and lateral pressure coefficient (CLP), which can serve as a guide for designing mining in similar geological and mining environments.

The working condition matching between the key equipment and the caving zone (RCZ) in the secondary mining of leftover coal, as well as the structural mode of roof fracture, have been studied through similar simulation experiments and finite element numerical simulation experiments [27,28]. It is believed that the main reason for the sudden increase in working resistance of the support in the mining area is that long key blocks cross the RCZ zone.

Hao H [29] conducted in-depth research on the evolution law of gas oxygen nitrogen adsorption coupling under goaf conditions based on Monte Carlo simulation and believed that the free state gas analysed in the goaf would affect the interaction between coal and air, thereby hindering the spontaneous combustion of residual coal.

For the phenomenon of roadway surrounding rock fragmentation and difficulty in supporting during the secondary development of residual coal resources, Chen Y and Shimada H team et al. [30–32] found that retaining roadway coal pillars with a width-to-height ratio of 1 or more is a key measure in maintaining the stability of roadway surrounding rock during the remining process of goaf residual coal.

In addition, Xca B., Sza B et al. [33–35] established a reasonable calculation model for residual coal and natural gas resources in abandoned mine goafs and conducted in-depth research on the impact mechanism of CH_4 storage and collection in the secondary development process of residual coal in goafs.

For the current situation of the recovery of coal resources left behind in the existing room pillar type goaf, high water material filling or flexible membrane pier pillar support is usually used to support the roof of the goaf. The high water material filling cost is high, and it is often difficult to adapt economically to the profit cost brought by residual coal mining. In addition, during the mining process, the shearer is difficult to cut high water materials with a hardness far higher than the coal seam. The method of flexible membrane pier column support also has limitations, such as high cost and limited support area. Therefore, the CRRM method is used to reshape the entire floor of the room column-type goaf to form a new long wall-type goaf, which has great potential for application and theoretical research in the local area [36].

The method of using inorganic high-water materials to fill the goaf and control the movement of overlying strata has been relatively mature in the first mining face. The strength, stability, and economy of the materials are suitable for mines that require filling mining methods [37]. However, it is still urgent to study and explore the complex roof and floor integrity conditions and the performance of mixing loose solid waste or loose coal during the operation of residual coal mining. This article focuses on the preliminary exploration of the method of using inorganic high-water materials to cement and fill loose coal and gangue into a pillar-type goaf to reshape the remaining coal in the goaf into a whole coal seam. It provides a theoretical basis for the ratio parameters of inorganic high-water materials, the control requirement parameters of roof rock layers, and the difficulties in construction technology.

2. Coal Remoulding and Replacement Mining Technology (CRRM)

2.1. Engineering Application Background of CRRM

To solve the contradiction between the recovery of coal resources left behind in a pillar-type goaf and the difficult matching of time and space between water sand filling and pipeline paste filling coal mining methods, as well as the poor economic efficiency, the author's team proposes the concept of "coal seam reshaping and replacement filling" in a pillar-type goaf, which means that the coal or gangue produced by the excavation face or other mining faces is filled into the goaf through a dumping machine and initially compacted. The use of inorganic high-water materials to cement and form loose coal (gangue) bodies achieves the goal of filling the free space of the old goaf again to form a hole, reshaping the complete coal seam, and effectively controlling the roof rock layer of the old goaf. It has the economic advantages of a fast construction period, no impact on the quality of the recovered coal, safety and reliability and is difficult to compare with other methods [38–40].

The engineering background shown in Figure 2 is a pillar-type goaf residual coal mining face arranged in the #5 coal seam of a coal mine in Shenmu City, Shaanxi Province.

The working face has a length of 1529.4 m, a width of 193.5 m, and an area of 2.96 × 105 m^2, with an average coal thickness of 5.4 m. The coal seam has a low coefficient of variation and is a horizontal coal seam. The average width of the two empty alleys in the middle is 6.12 m, and there is a total of 21 connecting alleys, with an average width of 6.12 m. After deducting the total amount of coal extracted from the goaf, the remaining minable coal in the working face is approximately 1.68 × 106 tons, and the coal quality is ultralow ash, ultralow sulfur, ultralow chlorine, high calorific value, high volatility, medium fixed carbon, high quality and easy to select nonstick coal. The burial depth of Coal Seam #5 is 140 m, and the characteristics of the roof and floor of Coal Seam #5 are shown in Table 1. The direct roof of Coal Seam #5 is medium hard and dense 5.2 m fine sandstone, the basic roof is 18.7 m medium hard and stable fine sandstone, and the floor is siltstone and fine sandstone, as shown in Figure 3. According to the preliminary analysis, the direct roof is hard and easily falls with mining. The basic roof is thick and hard and can form a good protective structure for the stope under the condition of crustal stress with a buried depth of 140 m.

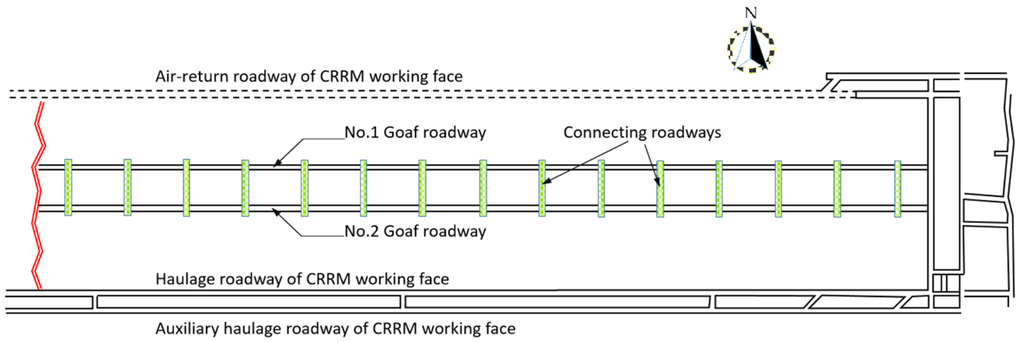


Figure 2. Mining layout scheme of CRRM working face.

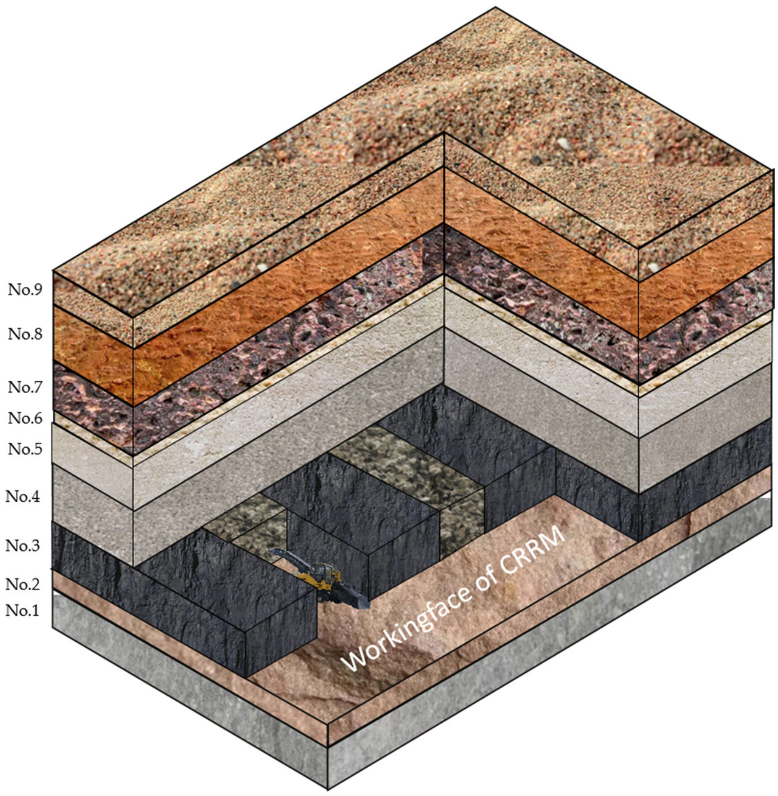


Figure 3. Spatial comprehensive geological histogram of CRRM working face in the engineering field.

Table 1. Rock layer name, annotation to Figure 3.

Stratum Name & Hermeneutics	Lithology	Thickness (m)	Feature Description
	Macroporous soil	50.0	Sediments mainly composed of silt and containing a certain proportion of fine sand, extremely fine sand, and clay particles
	Laterite	35.0	Reddish brown with high water content, low density, and high strength
9	Siltstone #1	15.0	Contains more quartz, followed by feldspar and rock debris, with a hard texture and low density
8	Fine-grained sandstone	18.7	It is generally light grey, containing feldspar and a small amount of rock debris
7. Main roof	Medium grained sandstone #1	21.3	Mainly fine sandstone, grey, dark grey with thin layer of siltstone
6. Immediate roof	Medium grained sandstone #2	5.2	Fine-grained sandstone is mainly grey and light grey, with medium sorting, containing muscovite flakes and dark minerals intercalated with thin layers of siltstone, in an interlayered and wavy bedding.
5. Coal seam	Coal	5.4	Proctor hardness reaches 2.38, thickness is stable
4. Immediate floor	Siltstone #2	20.0	Light grey, intercalated with thin layers of fine-grained sandstone, interbedded, containing fragments of plant fossils.
3. Main floor	Argillaceous rocks	30.0	Grey, light grey, well sorted, locally calcareous cementation, containing a small amount of plant fossils, wavy bedding.
2. Refilling bearing structure	Inorganic high water filling material + scattered coal/Gangue	5.4	Refill the roadway space via two methods: accumulation compaction grouting or mixing water spray cementation
1	Crawler gangue filling machine		Suitable for all-around filling of coal mine roadways, with the function of ejection compaction, high filling density, and good roof connection effect

As shown in Figure 4, the spatial relationship between the CRRM process working face of Coal Seam #5 and the eastern old goaf is modelled. After forming longwall mining conditions in the working face, there are two reshaped coal tunnels formed by the reinforcement of loose coal in the near central position. After applying ground stress in the finite element numerical simulation model, it was found that the peak stress values of the roof of the two empty tunnels are relatively large, and the relative displacement of the two sides is also relatively large.

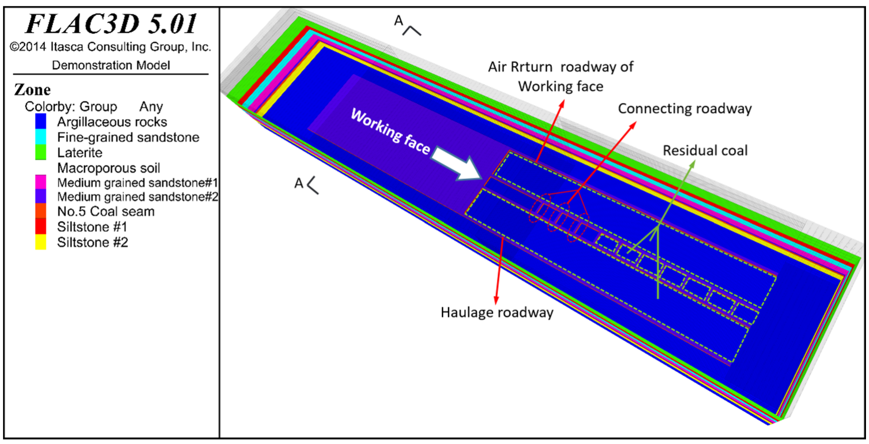


Figure 4. *Cont.*

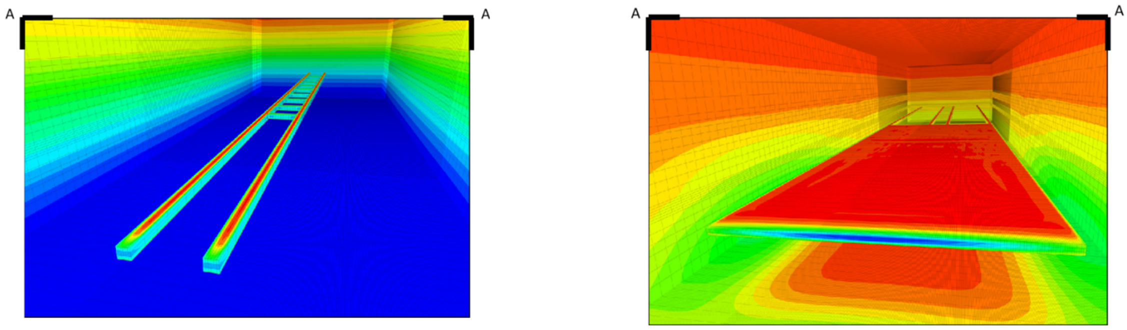


Figure 4. 3D schematic diagram of excavation space and mining sequence in the mining area. (A—A represents the profile).

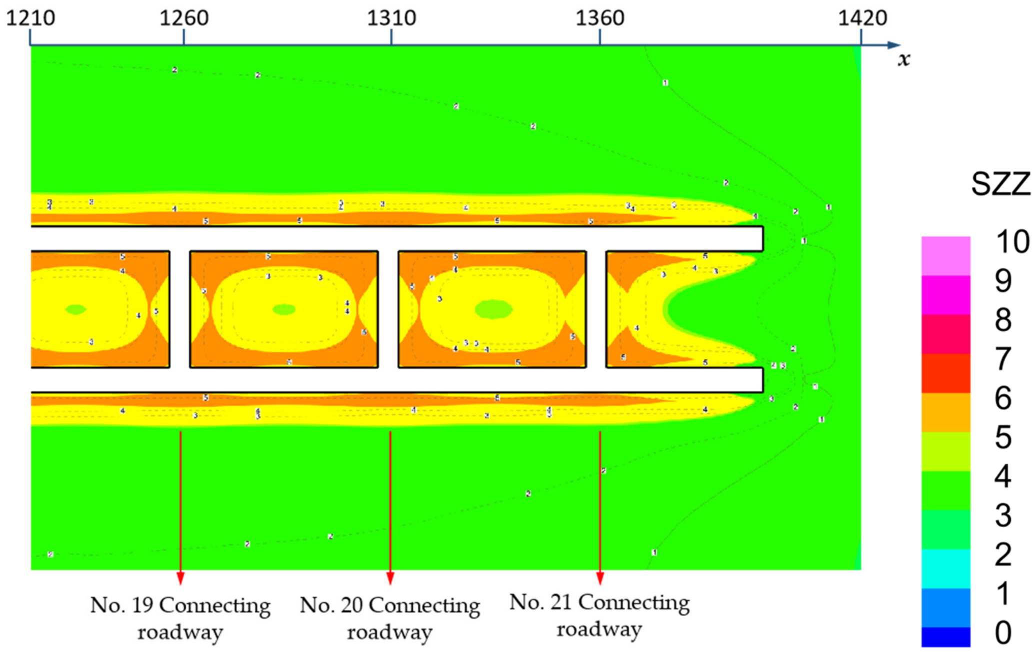
2.2. Analysis of the Mechanical State of the Surrounding Rock in the Closed Goaf

The eastern goaf of the #5 coal seam working face is a typical pillar-type goaf formed before 2009. The No. 1 goaf extends from west to east with a length of 937 m and a width of 6.12 m. The No. 2 goaf is arranged parallel to the No. 1 goaf, with a length of approximately 945 m. There are 21 connecting roadways and 22 interval coal pillars between the two goafs, with an average width of 6.12 m. The average recovery rate in this area is less than 23%, and nearly 70% of the coal resources urgently need to be recycled and utilized. Due to the burial depth of coal seam #5 being approximately 140 m, the internal stress of the surrounding rock and connecting roadway pillars in the eastern goaf is relatively small, and the mechanical properties of the coal in this area are good, belonging to the medium hard coal seam. Through borehole television observation, it was found that after nearly 14 years of stress release and full displacement of the surrounding rock towards the free space, the retaining state of the goaf surrounding rock is good, and there is no significant difference in the amount of roof subsidence and the relative movement of the two sides of the connecting roadway compared to before the goaf closed.

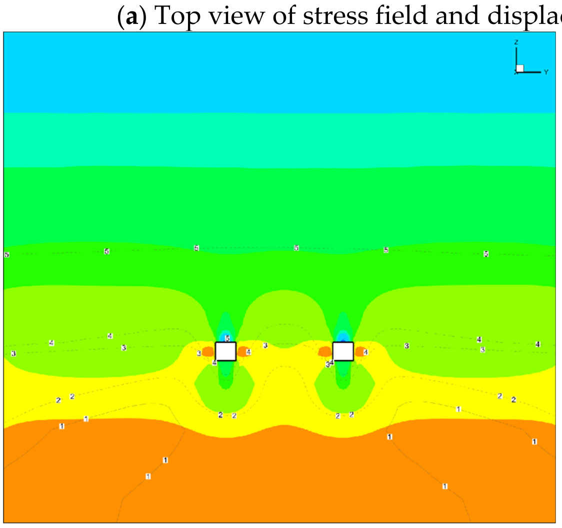
However, considering the secondary disturbance caused by the roadway excavation in the working face and the stress redistribution impact caused by the third disturbance caused by mining on the eastern goaf, in combination with local coal mining safety policies, laws and regulations and according to the latest version of coal mine safety regulations on goaf management and the relevant regulations of the Shaanxi Provincial Emergency Department on goaf management, it is necessary to strictly detect and explore the internal roof situation of the goaf. The content of toxic and harmful gases, as well as the water damage situation of the surrounding rock layer in the goaf, must be strictly verified and approved before the goaf can be disturbed again, and goaf operations are strictly prohibited. Therefore, before designing the parameters related to the CRRM process, it is necessary to estimate and evaluate the impact of mining disturbance on the surrounding rock of the #5 coal seam goaf and the CRRM working face when passing through the goaf through measurement and numerical simulation experiments. The numerical simulation experimental model is shown in Figure 2. Considering the excavation length of the stope roadway and the provisions in the Adhémar Jean Claude Barré de Saint-Venant Principle [22], the external boundary size of the model is 1500 m × 500 m × 200 m long × wide × high), and the model height ranges from the basic floor to the macroporous soil layer on the surface. After excavation, the natural gravity of each part of the rock layer is shared and transmitted to the surrounding rock of the mining site, with fixed horizontal boundary constraints. Based on the actual mining geological conditions, two empty tunnels and 21 connecting tunnels in the east were first extracted, and the built-in Fish language [23] was used to fully consider the full impact of a 14-year time step on the stress redistribution and displacement of the surrounding rock in the goaf. After excavation balance, the calculation results showed that the top view slice of the goaf location roof is shown in Figure 3.

In Figure 5, it can be seen that the distance between two adjacent alleys is 50 m, and the leading peak stress of the alleys reaches about 4.28 MPa, with an impact range of about

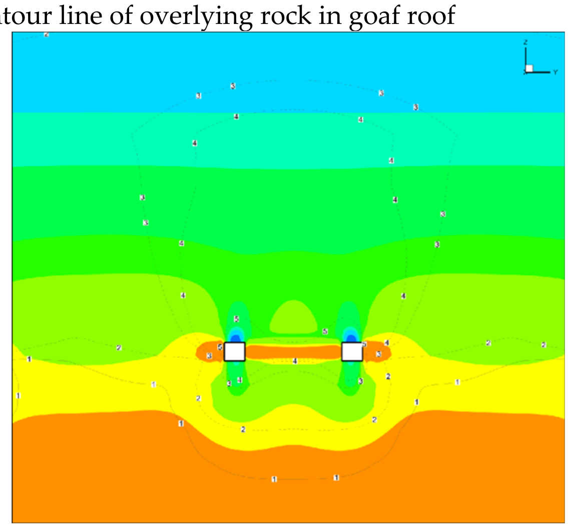
2.2 m. The top view of the eastern goaf (a) and the cross-sectional map of the surrounding rock state of the goaf are comprehensively analysed. The colour cloud map in the figure represents the variation law of the vertical stress field, and the contour line represents the displacement; (b), (d) and (f) are the stress displacement states of the surrounding rock in the middle of the left coal pillar at 1235 m, 1285 m, and 1335 m, respectively; (c), (e) and (g) are 1260 m, respectively. The stress displacement state of the surrounding rock near the free surface of the excavation of the connecting roadway near the coal pillars at 1310 m and 1360 m positions.



(**a**) Top view of stress field and displacement contour line of overlying rock in goaf roof

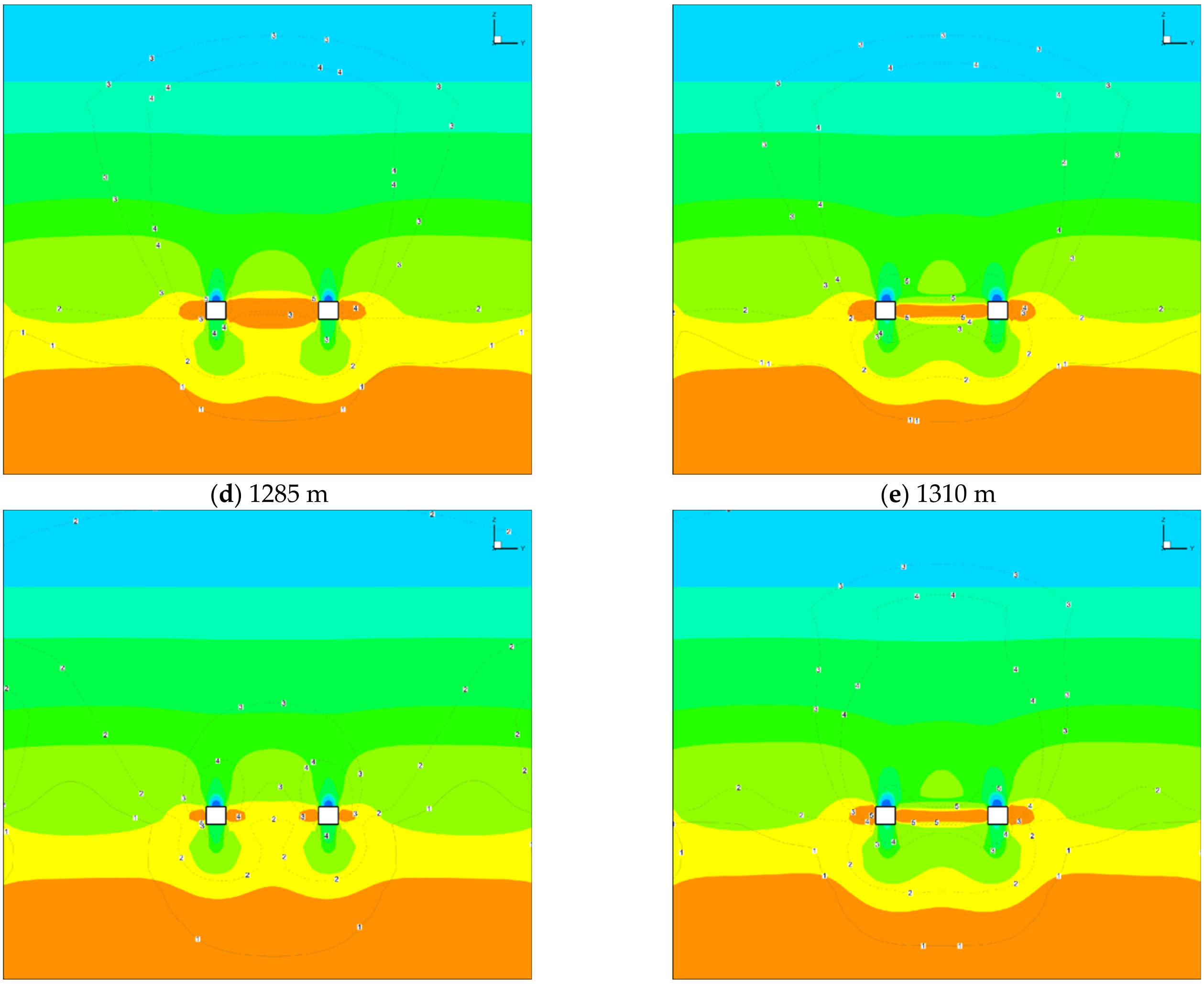


(**b**) 1235 m



(**c**) 1260 m

Figure 5. *Cont.*



(**d**) 1285 m (**e**) 1310 m

(**f**) 1335 m (**g**) 1360 m

Figure 5. Surrounding rock in the middle of the empty roadway (**b**,**d**,**f**) and state of the connecting roadway surrounding rock.

Through an analysis of the evolution law of the vertical stress displacement field, as the section position of the tunnel extends from west to east (x: 1235 m → 1285 m → 1335 m), it is not difficult to see that the stress concentration range on both sides of the tunnel first increases and then decreases, and the peak stress value reaches approximately 5.32 MPa. The maximum displacement occurs at the top of the roadway, with a peak displacement of approximately 0.5 m, and the mining disturbance, with a displacement of 0.2–0.4 m in the surrounding rock of the roadway, also shows a trend of first increasing and then decreasing in the range of influence on the top and bottom of the roadway. Analysis of the stress-strain displacement variation law of the surrounding rock of the two roadways extending from west to east indicates that the stress and displacement peaks in the central area of the roadway are greater than those at the cut and stop line positions. The characteristics exhibited are significantly different from the stress state changes of the surrounding rock of the roadway exhibited by traditional longwall mining techniques. Therefore, it is of great significance to simulate the surrounding rock state of the pillar goaf before remining.

As the profile position of the remaining coal pillar extends from west to east (x: 1260 m → 1310 m → 1360 m), the peak stress of the coal pillar near the connecting roadway reaches approximately 4.27 MPa, and the influence range of the peak stress also shows a pattern of first increasing and then decreasing. The development range of the 0.2–0.4 m displacement contour line first increases and then decreases, and the development height affects the basic top #1 medium-grained sandstone, and the surrounding rock displacement reaches 0.5 m, penetrating the coal pillar between the connecting roadways. The average stress value of the residual coal pillar near the connecting roadway is smaller than that of the surrounding rock in the middle of the empty roadway, while the displacement is greater than that in the middle of the empty roadway. Therefore, the control effect of the filling body in the connecting roadway on the top, bottom, and two sides of the surrounding rock, as well as the support strength and deformation capacity, is crucial. It directly affects the safety of the mining site, the operational efficiency of the coal mining machine, and the pushing efficiency of the hydraulic support when CRRM is used to reshape the coal seam.

Furthermore, it is necessary to study the influence of advanced support stress during secondary mining on the surrounding rock state of the goaf. The goaf is selected as an unsupported and unfilled bare goaf state for simulation to obtain the effect of secondary mining disturbance under adverse conditions and obtain suitable guidance for the strength parameters of the filling material.

2.3. Selection of the Simulation Method

Figure 6 shows that as the secondary mining face approaches the eastern goaf from the 25 m position, the goaf roadway is affected by advanced stress within a range of approximately 27 m, with a maximum peak value of 5.72 MPa at a distance of 2.4 m from the coal wall of the working face. Moreover, as the working face continues to advance to the front of the goaf, the maximum displacement of the coal pillars between the goafs increases from 0.407 m to 0.54 m, which indicates that the advanced stress superposition disturbance caused by secondary mining will further have a relatively small adverse impact on the stability of the goaf coal pillars.

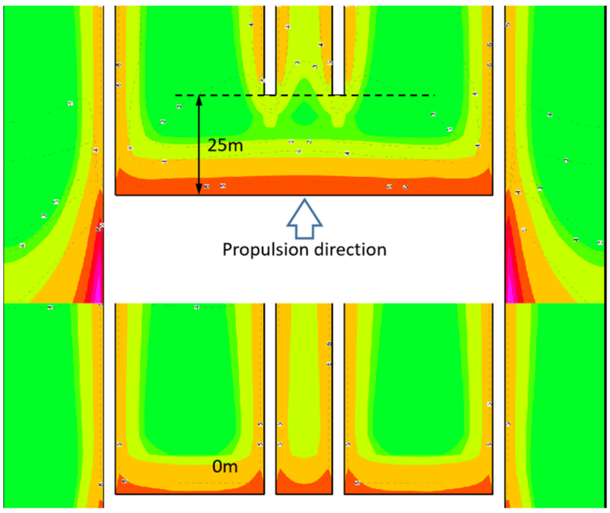


Figure 6. Evolution of surrounding rock mechanical state when the CRRM working face gradually advances towards goaf position.

2.4. Preliminary Determination of the Overall Strength of the Required Filling Materials

The migration of roof rock layers and redistribution of stress caused by secondary mining require that the materials filled in the goaf not only timely limit the displacement of the roof and two sides but also bear the high roof force caused by the disturbance of the advanced support pressure during remining [26].

It is also necessary to consider that after the coal seam is reshaped into a long wall working face, when the shearer cuts, the cohesive force and stiffness of the filling material should not bring excessive working strength to the cutting teeth of the coal mining machine. Furthermore, considering the chemical pollution caused by coal washing to the environment, the filling material is more suitable for selecting a certain proportion of loose coal and inorganic high-water cementitious materials to mix and form a whole.

In consideration of the above aspects, the optimal scheme is when the overall mechanical properties of the bulk coal mixed material are similar to those of the original coal seam. Then, the rock mechanic parameters of middling coal under the geological conditions in this paper are calibrated in the laboratory, and the target properties of the bulk coal mixed filling material that needs to be achieved are as follows. 1. The uniaxial compressive strength (UCS) reaches 1.5 MPa. 2. The cohesion C reaches 1.3 MPa. 3. The proportion of loose coal quality should exceed 80%. 4. The damage time shall not be less than 500 s.

3. Maintenance Mechanics of Bulk Coal Cementitious Materials in the Laboratory

There are usually two ways to add cementitious materials to the bulk coal pile for reinforcement during on-site construction. 1. Premix solid powder inorganic high-water cementitious materials with water and inject them into the bulk coal pile through short pipe grouting. 2. Mix solid powdery inorganic high-water cementitious material with loose coal and lay it layer by layer into the goaf connecting the roadway and the interior of the roadway, and spray with water to form cementitious material until it reaches the top. It is difficult to control the grouting radius and cementation range when loose coal blocks are used.

To truly replicate the cementitious process of loose coal in the laboratory, inorganic high-water cementitious materials in the form of solid powder were mixed with loose coal and placed layer by layer in a 10 cm $\times$ 10 cm $\times$ 10 cm specimen curing box and soaked with water in layers. After seven days of curing, uniaxial loading mechanical experiments were conducted to investigate the influence of different factors (bulk coal particle size, proportion of inorganic high water cementitious materials) on whether the overall mechanical properties of bulk coal cementitious materials can reach the target reference value.

3.1. Specimen Preparation and Apparatus for Tests

For the prepared and cured specimens of different schemes, in the uniaxial compressive rock mechanics experimental device shown in Figure 7, after the CRRM filling material is filled into the gob roadway and cross roadway in the simulated engineering practice, when the CRRM forms the whole layer of mining of the working face, under the disturbance of the advance abutment pressure, the stress of the surrounding rock of the gob roadway and cross roadway is redistributed again, and the roof and floor are relatively moved in.

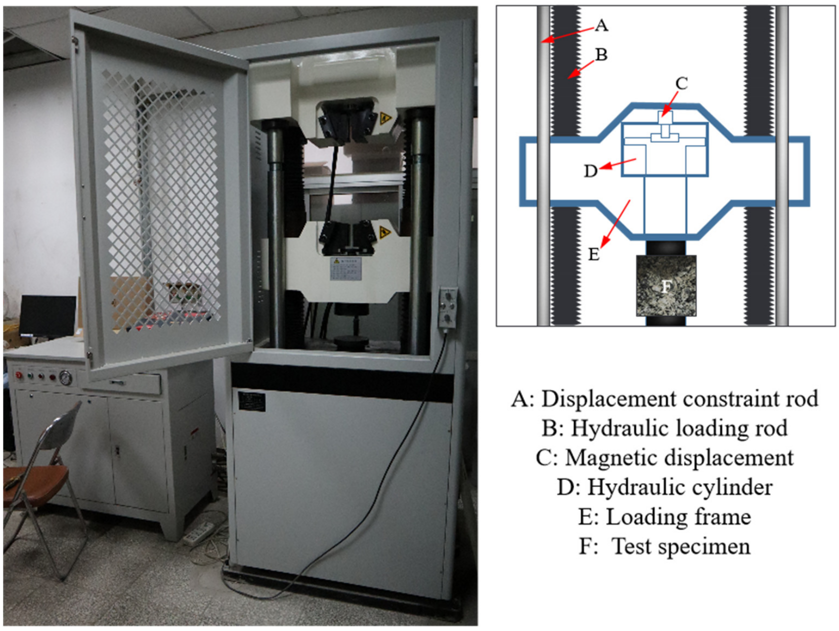
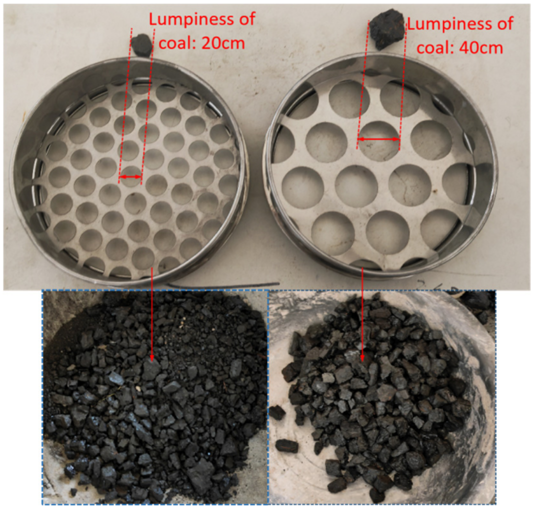


Figure 7. CRRM material specimen strength testing device.

When using uniform, similar simulations as in the previous numerical simulation, the relative moving speed of the roadway roof and floor is 0.2 m/year, the relative moving speed of two trays under the action of the oil pump of the single axle hydraulic press is set to 0.05 mm/min, and the size of the test piece is set to a 100 × 100 × 100 mm standard specimen, as specified by the International Rock Mechanics Association, as shown in Figure 8.



Screening process

Preparation and maintenance process

Figure 8. Four processes of screening, mixing, curing, and demoulding for CRRM specimen preparation.

The experimental middling coal sample is taken from the coal bunker of a coal mine located in Shenmu City, Shaanxi Province, where the CRRM process will be applied in this engineering background. Sieves with particle sizes of 2 cm and 4 cm are used to separate the raw coal and specimen preparation and orthogonal experiments are conducted based on the size of the loose coal, the proportion of loose coal (coal to inorganic cementitious materials and water), and the curing time (Figure 6). The specimen preparation parameters are recorded in Table 2.

Table 2. Orthogonal experimental plan data record table.

Specimen Number	Lumpiness of Coal	Proportion of Coal Quality	Curing Duration	Compressive Strength
1	2 cm-100%	95%	3 d	
2	2 cm-50% and 4 cm-50%	90%	7 d	
3	4 cm-100%	80%	14 d	
...				

3.2. Analysis of CRRM Material Strength Experimental Results

After conducting a total of 27 orthogonal experiments with three factors and three parameters, four sets of specimens with a dynamic failure time exceeding 500 s and a hardness close to 1 MPa were obtained. Among them, the failure time of sample 1 (loose coal block size 2 cm 100%—loose coal proportion 80%—curing 14 d) was 527 s, that of sample 2 (loose coal block size 2 cm 100%—loose coal proportion 90%—curing 14 d) was 818 s, and that of sample 3 (loose coal block size 2 cm 50%—loose coal proportion 90%—curing 7 d) was 1289 s. The failure time of sample 4 (with a particle size of 2 cm 100%—a proportion of 95%—a curing time of 7 d) was 617 s. The entire process curve of uniaxial compressive strength testing is shown in Figure 9.

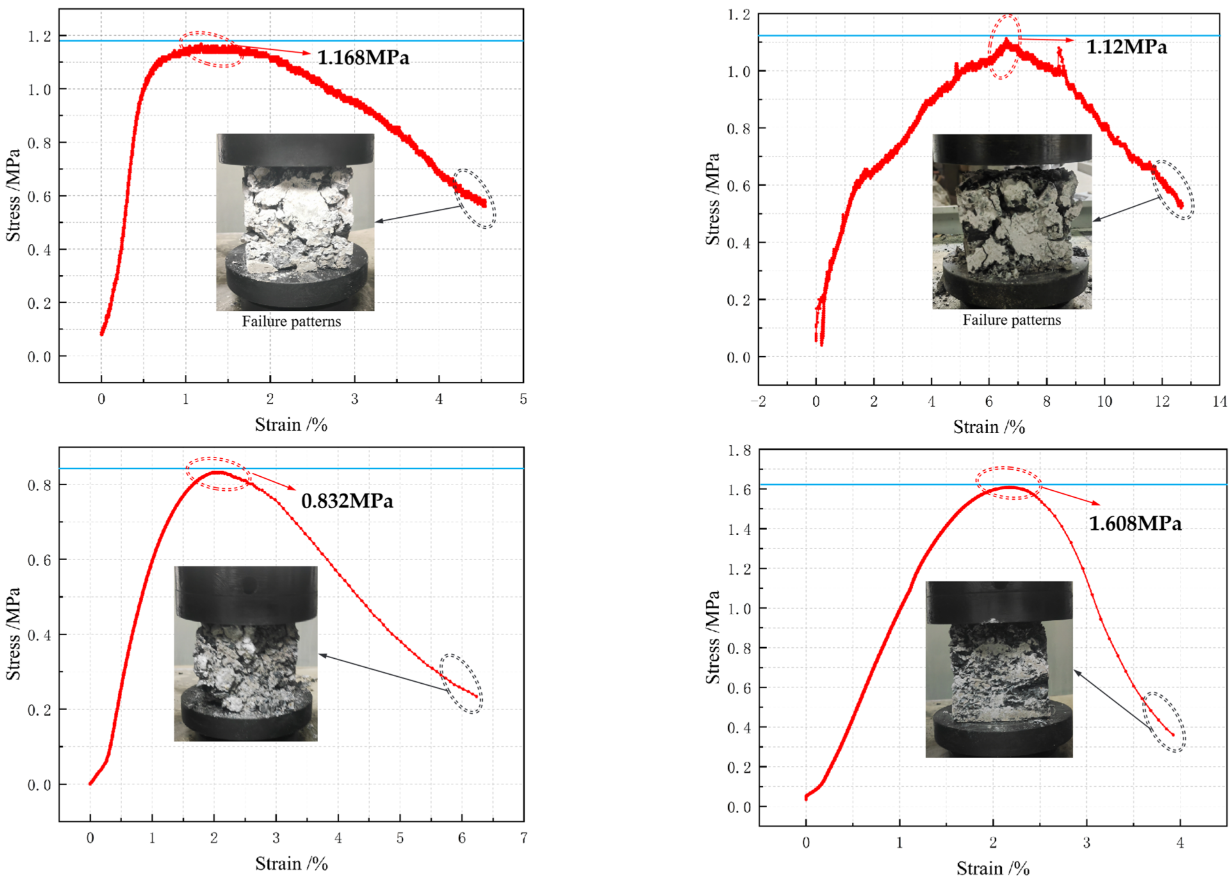
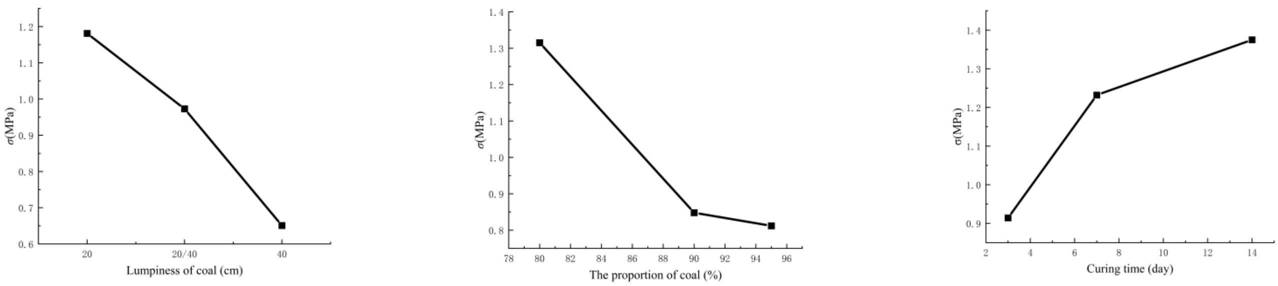


Figure 9. The stress-strain curve characteristics of four sets of specimens that met the dynamic response characteristics (specimen #s 1, 2, 3 and 4).

It can be seen that among the four samples that met the dynamic failure duration requirement, the strength of sample #1, sample #2, and sample #4 all exceeded 1 MPa, and the strength of sample #4 reached 1.6 MPa. The strength of sample #4 also exceeded 1 MPa during a considerable post-peak strain process. Further analysis was conducted on all samples, and the experimental data of 27 samples were divided into three groups based on the differences in coal block size, coal content proportion, and curing time to calculate the average value. The evolution and influence of three influencing factors on the strength of CRRM specimens can be preliminarily obtained, as shown in Figure 10.



(**a**) Lumpiness of coal—σ (**b**) Proportion of coal—σ (**c**) Curing duration—σ

Figure 10. The influence of three main influencing factors on the strength of CRRM materials.

As the particle size of loose coal increases from 2 cm in size to 50% of 4 cm in size, the average strength monotonically decreases. The average strength of the two stages decreases by 17.6% and 33.1%, respectively. As the proportion of coal content increases from 80% to 90% and eventually reaches 95%, the average strength of the two stages decreases by 35.5% and 4.2%, respectively. During the process of extending the maintenance period from 3 days to 7 days and finally to 14 days, the average strength of the two stages increased by 34.8% and 11.6%, respectively.

Based on comprehensive analysis, it was found that under the environmental protection policy requirements for coal impurity separation in the washing process, it is appropriate to choose a ratio scheme with a coal quality ratio of 90% or more. This requires minimizing the coal particle size and increasing the curing time to 7 days, which serves as a theoretical guide for conducting on-site large-scale CRRM practical engineering material solidification and reinforcement experiments.

4. Ultra-Large Size Similarity Simulation Experiment of CRRM Materials

To promote the above CRRM coal seam reshaping and remining technology to the engineering application stage, on-site experiments were conducted on the cementitious strength of oversized CRRM remining filling materials. To avoid interference from unpredictable factors such as wind direction and temperature during the experiment, two blocks with a 2.2 × 2.2 × 2.2 m displacement limited boundary mould (as shown in Figure 11) are used, and sieves with the same particle size of 20 cm are mixed and placed in layers into the mould. After 7 days of standing and curing indoors in adjacent positions, samples are taken for strength testing after demoulding.

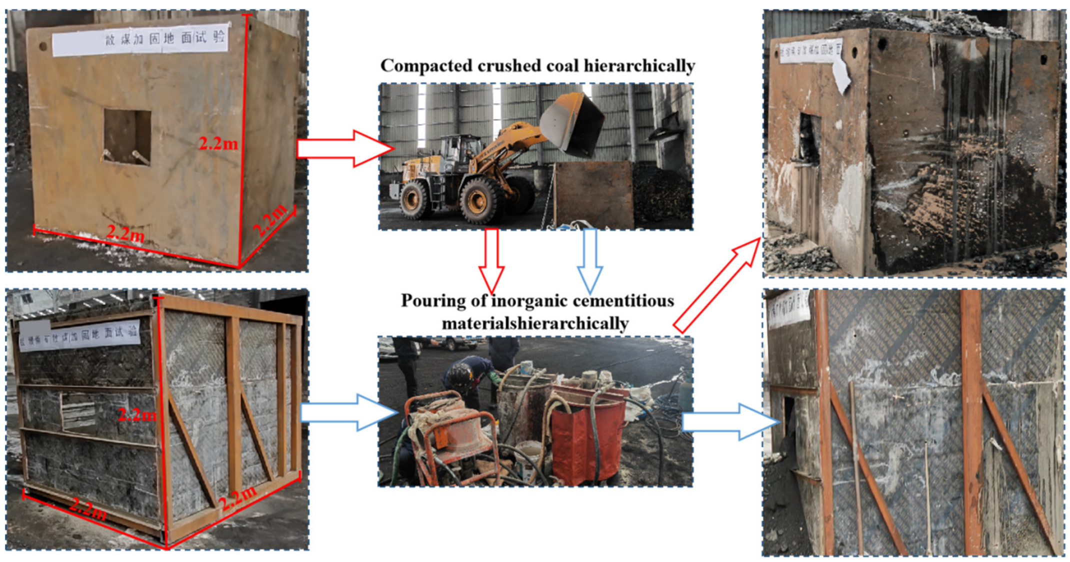


Figure 11. Experimental process scheme for the strength test of cured ultra-large CRRM materials.

4.1. Development of On-Site Experimental Ideas and Construction Techniques in Engineering Practice

1. During the on-site construction process, the raw coal blocks collected from the #5 coal seam in the coal bunker were first screened (the 2 cm particle size in the laboratory ratio was enlarged to the actual 20 cm particle size), and the screened coal blocks were filled layer by layer into the oversized mould.

2. The cementitious material with strong fluidity was mixed at a 1:2 ratio with water and evenly poured onto the surface of the coal block layer that was filled into the mould.

3. Within 2 min of the rapid solidification effect of the cementitious material, the second layer of coal blocks was quickly filled into the upper surface of the first layer of the coal block cementitious material mixture layer and preliminarily compacted it.

4. After filling the mould with cementitious coal blocks in layers according to steps 1–3, following the characteristics of the relative movement of the top and bottom of the tunnel, the upper free boundary was compacted twice and cured at a constant temperature and wind speed indoor environment for 7 days.

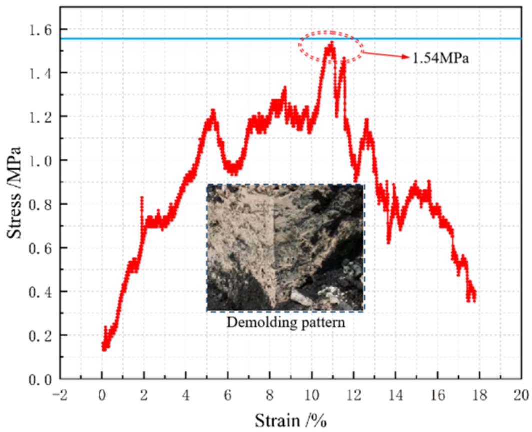
As shown in Figure 11, a method to obtain ultra-large CRRM simulation test blocks was achieved. During the test block preparation process, it was found that to ensure that the slurry of the cementitious material did not run along the weak surface of the coal block during the strong fluidity stage, a plastic film needs to be laid inside the mould, which also provides empirical guidance for on-site construction.

4.2. Analysis of the Strength of the Results of the Ultra-Large-Scale Similarity Simulation Experiment Demoulding Sampling Experiment

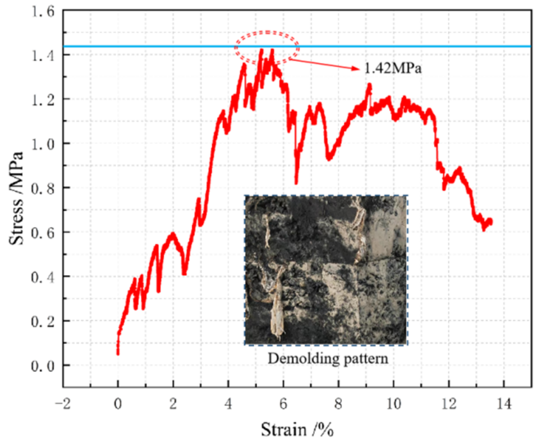
After 7 days of curing, it was found that the overall moulding effect of CRRM loose coal cementitious material was good, and no collapse or other damage occurred after removing the fixed boundary limit. The model was broken using a pneumatic drill, and the middle position with lower strength was selected as the strength analysis sample. Two oversized specimens, No. 1 and No. 2, were each trimmed to form a 20 × 20 × 20 cm CRRM material test block for the laboratory rock mechanics strength test.

Analysis of the stress-strain curves of the two test blocks from No. 1 and No. 2 revealed that the overall uniaxial compressive strength reached 1.54 MPa and 1.42 MPa, respectively (Figure 12, The red dotted line represents the uniaxial pressure test data, and the blue line represents the peak intensity position marking line), which can meet the support strength requirements for the surrounding rock of the tunnel obtained from previous research. Moreover, the true characteristics reflected by its ultra-large size show that the strong heterogeneity of small laboratory specimens causes them to be difficult to model, and the stress-strain curve oscillates significantly during the loading process. Both the prepeak and postpeak stages exhibit strong oscillation characteristics, and the residual strength stage still exhibits good load-bearing characteristics, which is a positive attribute for the on-site application of the CRRM process.

When the CRRM material plays a supporting role on the top and bottom of the goaf under working conditions, it works in conjunction with the newly added anchor rods, anchor cables, anchor mesh, and spraying materials inside the goaf. The CRRM material mainly plays a role in limiting displacement on the top and bottom of the goaf and reshaping the front coal wall that is scattered throughout the goaf during the mining process, forming an overall coal seam for the formation of a long wall working face for bidirectional coal cutting by the coal machine during mining. Therefore, based on the comprehensive analysis of the strength results of laboratory experiments and on-site large-scale similar simulation experiments, it can be concluded that the CRRM material can meet the filling strength requirements of the coal seam reshaping resource replacement mining process by selecting an inorganic high water cementitious material with a particle size of 20 cm and a mass of 10% by weight of mixed coal blocks and maintaining it for 7 days.



No. 1 Extra large specimen



No. 2 Extra large specimen

Figure 12. Stress-strain curve of the ultra-large CRRM specimen.

5. Conclusions

Coal seam reshaping replacement type abandoned coal mining technology (CRRM) was proposed, and finite element simulation experiments on the overall surrounding rock state of the mining site and strength experiments on CRRM loose coal cementitious filling materials were carried out based on the actual engineering background on site. The aforementioned stages were used as theoretical parameters to guide on-site maintenance experiments on oversized CRRM materials. The main conclusions of this study are as follows:

(1) When designing the CRRM process plan, it is necessary to determine the stress and displacement status of the surrounding rock of the old goaf and the connecting roadway through a numerical simulation. In shallow coal seams, the stress of the surrounding rock of the goaf roadway is generally not high, and the peak stress concentration coefficient is approximately 1.08. Therefore, the CRRM material mainly plays a role in limiting displacement in supporting the top and bottom of the goaf. When combined with anchor rod anchor cable anchor mesh support, the strength requirement should meet 1.5 MPa.

(2) As the particle size of coal increases, the strength of the CRRM material decreases accordingly. The strength of the CRRM material decreases with an increasing proportion of the bulk coal mass. The increase in curing time will lead to an increase in the overall strength of the CRRM materials.

(3) The maintenance experiment of oversized CRRM material shows that the on-site large-sized filling block is different from the 10 cm. The size effect of the 10 cm specimen brings significant strength differences, and the characteristics of the prepeak and postpeak curves are different from those obtained in laboratory experiments. In the next step of the experiment, microscopic research will be conducted to explore the refinement differences in oversized and small-sized CRRM specimens under an electron microscope, which can improve the strength properties of the specimen and make it suitable for mines containing residual coal resources with more complex geological conditions.

Author Contributions: L.L. and X.Z. wrote the main manuscript text and dealt with all figures, B.H. prepared Figures 5 and 6, and S.L. conducted a preliminary translation of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the National Natural Science Foundation of China project "Research on the Time Effect Mechanism and Dynamic Response of Overburden goaf Coal Pillar Synergistic Action and Residual Coal Re mining", 52074291, the National Natural Science Foundation of Surface Project of China, 51774289 and the National Natural Science Foundation of the Youth Science Foundation of China, 51404270.

Data Availability Statement: The results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration by another publisher.

Conflicts of Interest: The authors declare that there are no conflict of interest regarding the publication of this paper.

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