The Sustainable Development of Aged Coal Mine Achieved by Recovering Pillar-Blocked Coal Resources

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Abstract: China faces the problem of depletion of its coal resources, and a large number of mines are becoming aged mines. Demand for coal, however, still increases due to the growth of China’s economy. Energy shortage might restrict the sustainability of China’s national economy. As one contribution to a solution, this paper proposes the innovative exploitation method of solid backfill coal mining (SBCM) technology to exploit parts of pillar-blocked (residual coal pillar resources under industrial square, RCPRIS) that protect industrial facilities. Thus, blocked coal resources may be converted into mineable reserves that improve the recovery ratio of mine resources. Also, waste would be removed from the surface reducing hazards of environmental pollution. Based on the case of the Baishan Coal Mine in Anhui, China, numerical simulation is used to study the size of shaft-protecting coal pillars (SPCP) required at different backfill ratios. Results show that the disturbance to a shaft caused by exploitation decreases with the increase of the backfill ratio. When using SBCM to exploit RCPRIS under the condition of 80% backfill ratio, compared with the caving method, a lot of pillar-blocked coal resources would be freed. The life of Baishan Coal Mine would be prolonged, resulting in appreciable social, environmental, and economic benefits.

Keywords: Pillar-blocked coal resources; exploitation; sustainability; aged coal mines; solid backfilling coal mining; benefits

1. Introduction

Owning large coal reserves, China is the largest producer and consumer of energy in the world. The rapid economic development and the improvement of people’s living standards have led to an increase in energy demand of China [1]. The fact that coal is considered as the primary energy source is unlikely to change for a long time according to China’s national conditions. At present, two major problems exist in China’s energy: First, with a large number of mines are becoming aged mines, China is now facing the problem of depletion of coal resources [2–4]. On the other hand, the demand of coal would increase in the future with the foreseeable growth of China’s economy [5–7]. China’s coal demand was predicted for 4.4–4.8 Gt in 2035 [8]. Obviously, there is a contradiction between the two problems, which will restrict the sustainable development of China’s national economy and coal industry seriously. Compared with increasing coal production, recovering pillar-blocked coal resources is more advantageous. It is the ideal solution because it can increase the production of coal and delays
the depletion of coal resources at the same time. Pillar-blocked coal resources mainly refer to unmined coal pillars at the border of coal field, around the industrial square (refers to the area around the wellbore containing facilities and buildings related to production and life) or between the working faces. The pillar-blocked coal has been evaluated as valuable coal, and exploiting pillar-blocked coal resources is an effective way to help solve the problems [9–13]. In China, there are diverse and considerable pillar-blocked coal resources in the aged coal mines. In particular, with the characteristics of centralized distribution and adequate reserves, RCPRIS has great recovery value.

As a byproduct of coal mining, coal gangue is usually discharged as solid waste to the surface. By 2014, the accumulation of coal gangue in China had reached about five billion tons. Coal gangue have risen to the top of the ranking of industrial solid waste in China. In addition, coal gangue emissions are still growing at a rate of 150 to 200 million tons per year [14,15]. When the coal gangue is piled up to the surface, it not only occupies a large amount of land resources but also generates dust and toxic substances, which have serious impact on the ecological environment and human health [16–18]. At present, the comprehensive treatment of coal gangue is becoming an important undertaking to strengthen environmental protection and promote ecological environment sustainability.

SBCM is a mining technology that combines strata movement control and solid waste disposal [19]. It is a green extraction technique that deals with the challenges of coal gangue accumulating on the ground and coal mining under buildings, railways and water. In SBCM, while extracting coal, the solid wastes such as coal gangue is filled to the goaf at the same time. The main purposes of SBCM are to stabilize the overlying strata, reduce coal gangue accumulating on the ground and reduce the environmental pollution [20–23]. On the other hand, the excavation support in underground mining using coal gangue is still an issue due to the proper management of the roof and (maintenance of excavation stability) and the assumption of inter-room pillars [24]. In this paper, the solid backfill materials used in SBCM are mainly coal gangue and part of fly ash.

For the above problems, this paper proposes an innovative exploitation method of using SBCM to recycle RCPRIS. In SBCM, the coal gangue on the ground is backfilled to the goaf, and the RCPRIS can be exploited under the premise of the safety of the shafts and buildings, which can not only improve the recovery ratio of coal resources but also address the coal gangue on the ground and reduce environmental pollution. It is of great importance not only to promote the sustainability of aged coal mines but also to promote the sustainability of China’s social economy and ecological environment.

2. Engineering Background and Existing Problems

The Baishan Coal Mine was officially put into operation in 1977. The ground elevation is +28 m to +32 m and the mining area is an alluvial plain. The dip angle of the coal seam is from 3° to 20°, and the average is 8°. Coal seam #6 is the main workable seam with an average thickness of 2.95 m. The occurrence condition of coal seam is simple and stable. The initial reserves were 12.25 million ton, and the original design service life was 53 years. The coal mine was developed by vertical shaft and adopted the longwall mining method. With efficient and continuous production for more than 40 years, the remaining recoverable coal becoming less and less. The Baishan Coal Mine has become an aged mine and is facing the problem of coal resource depletion. There are 4.95 million tons of pillar-blocked coal resources in the Baishan Coal Mine, among which the RCPRIS are 2.4 million tons, and these account for 48.5% of all pillar-blocked coal resources. The RCPRIS has the characteristics of centralized distribution and adequate reserves. At present, it is an urgent work finding a scientific and efficient exploitation method to recycle the RCPRIS, which can prolong the mine life, improve mine production and promote sustainability of the Baishan Coal Mine.
The RCPRIS of the Baishan Coal Mine belongs to coal seam #6, with an average thickness of 3.0 m. The ground elevation of RCPRIS is −211 m to −158 m and the average burial depth is 188 m to 241 m. The size of the RCPRIS region is measured 740 m long and 720 m wide. There are three shafts in the region of the industrial square, which are the main shaft, the auxiliary shaft, and the maintenance shaft. The depths of the three shafts are all 248 m. The diameter of the main shaft is 4.4 m, and the diameter of the auxiliary shaft and maintenance shaft is 5.0 m. The shafts are supported by C35 reinforced concrete material with a thickness of 300 mm. The axial compressive strength σc of the shafts is 21.3 MPa according to laboratory tests. RCPRIS are left to protect the three shafts. The location of the Baishan Coal Mine and the area of RCPRIS are shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** The location of the Baishan Coal Mine and the area of RCPRIS.

The coal, rock and soil samples were collected from the surrounding area of Baishan Coal Mine industrial square. The processing and test of standard samples was completed at the State Key Laboratory of Coal Resources and Safe Mining of China University of Mining and Technology. The basic rock mechanical parameters of different strata were measured with uniaxial compression testing, point load splitting testing and variable-angle shear testing, as shown in Figure 2. The basic mechanical parameters such as density ρ, elastic modulus E, Poisson’s ratio μ, cohesion c, and internal friction angle φ were obtained. The test results of the basic rock mechanical parameters of different strata will provide parameter guidance for the following numerical simulation calculations. The results are listed in Table 1.

| Stratums         | Density/ kg·m⁻³ | Modulus/GPa | Compressive Strength/MPa | Cohesion/c | Internal Friction Angle/° |
|------------------|-----------------|-------------|--------------------------|-----------|--------------------------|
| Surface soil     | 1800            |             |                          | 6         | 0.1                      |
| Weathered sandstone | 2100          | 52.72       | 4.69                     | 25        | 0.26                     |
| Mudstone         | 2200            | 18.34       | 1.70                     | 10        | 0.1                      |

|  | Tensile Strength/MPa | Poisson's Ratio | Friction Angle/° |
|------------------|----------------------|-----------------|-----------------|
| Surface soil     | 6                    | 0.1             |                 |
| Weathered sandstone | 13               | 5.5             | 0.18            |
| Mudstone         | 11                  | 2              | 42              |

![Figure 2](image2.png)

**Figure 2.** Rock mechanical parameter test. (a) Uniaxial compression testing; (b) point load splitting testing; (c) variable-angle shear testing.
Table 1. The test results of the rock mechanical parameters.

| Stratums               | Density/kg m⁻³ | Compressive Strength/MPa | Tensile Strength/MPa | Elastic Modulus/GPa | Cohesion/MPa | Poisson’s Ratio | Internal Friction Angle/° |
|------------------------|----------------|--------------------------|----------------------|---------------------|--------------|-----------------|-------------------------|
| Surface soil           | 1800           | -                        | -                    | 6                   | -            | 0.1             | -                       |
| Weathered mudstone     | 2000           | 14.62                    | 1.27                 | 13                  | 5.5          | 0.18            | 42                      |
| Weathered sandstone    | 2100           | 52.72                    | 4.69                 | 25                  | 10           | 0.26            | 45                      |
| Mudstone               | 2200           | 18.34                    | 1.70                 | 10                  | 4            | 0.1             | 40                      |
| Weathered sandstone    | 2100           | 52.72                    | 4.69                 | 25                  | 10           | 0.26            | 45                      |
| Mudstone               | 2200           | 18.34                    | 1.70                 | 10                  | 4            | 0.1             | 40                      |
| Coarse siltstone       | 2100           | 38.14                    | 4.25                 | 25                  | 10           | 0.26            | 45                      |
| Fine siltstone         | 2500           | 71.85                    | 5.42                 | 30                  | 16           | 0.3             | 47                      |
| Mudstone               | 2200           | 18.34                    | 1.70                 | 10                  | 4            | 0.1             | 40                      |
| Siltstone              | 2100           | 43.61                    | 4.53                 | 25                  | 10           | 0.26            | 45                      |
| Coal seam              | 1400           | 2.46                     | 0.19                 | 8.51                | 3.5          | 0.2             | 35                      |
| Mudstone               | 2200           | 18.34                    | 1.70                 | 10                  | 4            | 0.1             | 40                      |
| Siltstone              | 2100           | 43.61                    | 4.53                 | 25                  | 10           | 0.26            | 45                      |

3. Methodology

The shaft serves as an important passageway connecting the surface and the underground, which is responsible for the ventilation, transportation, lifting, and personnel transportation of the mine. Shafts directly affect the production safety of the mine. There are three shafts in the industrial square of the Baishan Coal Mine. When exploiting RCPRIS with SBCM technology, exploitation disturbance on the shaft varies with the size of the shaft-protecting coal pillar. The main subject of this paper is to design a reasonable size of the shaft-protecting coal pillar, that will not only reduce the impact of exploitation on the shafts and ground buildings but also minimize the size of the shaft-protecting coal pillar and improve the recovery ratio of pillar-blocked coal resources.

3.1. The Basic Mechanism of SBCM

The main difference between the working face layout of SBCM and traditional fully mechanized mining is that the backfilling operation face is arranged on the side of the goaf in SBCM, and the hydraulic supports for SBCM replace the traditional hydraulic supports. The backfill conveyor is hanged on the back of SBCM hydraulic supports, and a compaction machine is also designed at the back of SBCM hydraulic supports. The backfill conveyor is used to transport the solid backfilling material to the goaf, and the compaction machine is used to make the solid backfill material fill up the goaf and reduce its compressibility at the same time. In SBCM technology, the backfilling operation and mining operation can be achieved simultaneously.

In SBCM, solid backfill materials such as coal gangue are crushed to a particle size of less than 50 mm and then transported through a vertical feed system to the underground surge bin. When needed, the solid backfill material can be delivered by underground conveyor system to the backfill conveyor, which is hung at the back of the SBCM hydraulic support. The backfill conveyor discharges the solid backfill material into the goaf. The transportation route of the solid backfilling material is as follows: material-feeding shaft → underground surge bin → underground transport system → backfill conveyor → goaf. Then, the compaction machines push back the solid backfill material into the goaf [20–22]. The simplified scheme of SBCM is shown in Figure 3.
In SBCM, the backfill effect is mainly determined by the backfill ratio $\phi$. The higher the backfill ratio, the better the backfill effect is and the smaller the deformation of surface buildings and structures is. After fully mining, the roof subsidence achieves a stable state, and the height of roof subsidence in this state is called the roof final subsidence $h_f$ [25–27]. The definition of the backfill ratio is shown in Equation (1).

$$\phi = \frac{h_0 - h_f}{h_0} \times 100\%$$  \hspace{1cm} (1)

where $\phi$ refers to the backfill ratio, $h_0$ refers to the mining height, and $h_f$ refers to the roof final subsidence.

During exploiting RCPRIS with SBCM, the backfill ratio is an important factor for designing a reasonable size of the shaft-protecting coal pillar. In this paper, the reasonable size of the shaft-protecting coal pillar under different backfill ratio conditions is studied by the numerical simulation method taking the Baishan Coal Mine as a case. The purpose of the study is to improve the recovery ratio of pillar-blocked coal resources by minimizing the size of the coal pillar under the premise of the shafts safety. In this study, the axial stress of the shafts is taken as the criterion for assessing the shaft failure.
When the axial stress begins to exceed the axial compressive strength 21.3 MPa, the shaft is judged to be damaged.

3.2. Numerical Simulation Process

3.2.1. The Establishment of Numerical Model

Based on the geological conditions of the region in which RCPRIS is located, a simulation model is constructed by ABAQUS6.12 software with dimensions of 600 m \( \times \) 600 m \( \times \) 248 m (L \( \times \) W \( \times \) H) [28]. The model is divided into 92,502 elements, and the meshes surrounding the shafts are more detailed to ensure high computational accuracy. The Mohr-Coulomb model is adopted for simulating the coal and rock. The physical mechanical parameters of each rock formation are determined by the test results, and the mining height is 3.0 m. In terms of the boundary conditions, Degrees of freedom of horizontal direction of the model’s four sides are constrained. Degrees of freedom of \( x,y,z \) directions of the model’s bottom are constrained. There is no boundary condition on the top surface of the model. The monitoring points of axial stress are set along the three shafts.

In the process of SBCM, when the solid backfilling material is filled into the goaf, the caving space of the roof is decreased, which is equivalent to the mining height being reduced. Based on this phenomenon, Miao and Zhang proposed the concept of equivalent mining height [20,21]. When the goaf is filled up, equivalent mining height is equivalent to the roof final subsidence \( h_f \). The equivalent mining height model in SBCM is shown in Figure 4. Therefore, the relationship between the equivalent mining height \( H_z \) and the backfill ratio \( \phi \) can be expressed by Equation (2).

\[
H_z = h_f = h_0(1 - \phi)
\]  

(2)

![The equivalent mining height model in SBCM.](image)

In the numerical simulation process of SBCM, the excavation method of equivalent mining height is usually adopted to achieve different backfill ratio conditions. The method is adopted in this study. For the coal pillar recovery process, it is planned to design four working faces, with a mining height of 3 m, and a daily advance of 7 m based on experience. After the filling material is filled into the goaf, there is inevitably a certain distance between it and the roof (the size is related to the filling equipment parameters, working surface conditions, etc.). As the overlying rock layer sinks, the roof gradually comes into contact with the filling body, and the filling body will undergo a certain vertical deformation under the action of force, and finally a relatively dense structure will be formed. When the backfill ratio is 50%, 80%, and 90%, the final filling height is 1.5 m, 2.4 m, and 2.7 m, respectively. Correspondingly, the equivalent mining heights are 1.5 m, 0.6 m, and 0.3 m respectively.
3.2.2. Design of Exploitation Scheme

The protection effect of the shaft-protecting coal pillar is studied in this paper, under different sizes of coal pillar and with different backfill ratios when using SBCM technology. Additionally, reasonable sizes of the shaft-protecting coal pillar under different backfill ratios are determined. In the numerical simulation process, excavations are implemented from the four sides of the model to the shafts in the center of the model, step by step. The design of exploitation schemes is shown in Table 2.

Table 2. The design of exploitation schemes.

| Schemes Number | Backfill Ratio (%) | Equivalent Mining Height/m | Protecting Coal Pillar Size/m |
|----------------|--------------------|-----------------------------|-------------------------------|
| #1             | 0                  | 264                         | #17                           |
| #2             | 220                | #18                         |
| #3             | 176                | #19                         |
| #4             | 0 (Caving method)  | 3.0                         | #20                           |
| #5             | 154                | #21                         |
| #6             | 110                | #22                         |
| #7             | 88                 | #23                         |
| #8             | 44                 | #24                         |
| #9             | 50                 | 1.5                         | #25                           |
| #10            | 264                | #26                         |
| #11            | 176                | #27                         |
| #12            | 154                | #28                         | #29                           |
| #13            | 132                | #30                         |
| #14            | 110                | #31                         |
| #15            | 88                 | #32                         |
| #16            | 44                 | 44                          |

3.3. Results Analysis and Discussion

When the backfill ratio is higher than 0%, due to the supporting effect of solid backfilling material on overlying strata, the movement of overlying strata is more moderated. Therefore, prior to the shafts being damaged, the change of the shafts axial stress is small. Therefore, for the schemes where the backfill ratios are not 0% (#9–#32), this paper only lists the results that the axial stress is obviously changed during the excavation process. The axial compressive stress judging the shaft damaged is 21.3 MPa. The depth profiles of axial stress of the Baishan shafts at different backfill ratios is shown in Figure 5.

As shown in Figure 5:

(1) When the size of the shaft-protecting coal pillar is the same, the axial stress of the shaft and the disturbance to the shaft caused by exploitation both decreased with the increase of the backfill ratio.

(2) For the backfill ratios of 0%, 50%, 80%, and 90%, the axial stress begins to exceed the axial compressive strength \( \sigma_c \) of the shaft when the size of the shaft-protecting coal pillar reached 176 m, 154 m, 132 m, and 110 m, respectively. At that point, the axial stresses reached 22.02 MPa, 25.44 MPa, 30.82 MPa, and 167.3 MPa, respectively, and shaft failure begin to occur. Therefore, the reasonable sizes of the shaft-protecting coal pillar for the four backfill ratios are recommended to be in the ranges of 220–176 m, 176–154 m, 154–132 m, and 132–110 m, respectively.
(3) The axial stress of the shaft increases with the decrease of the size of the shaft-protecting coal pillar, and the axial stress increases with the depths of the shaft. The axial stress shows little variation within the unconsolidated layers but increases significantly during the transition to bedrock. In the bedrock, the axial stress fluctuates dramatically due to the differences of the mechanical properties between the rock formations. Furthermore, the axial stress of the shaft in hard rock formations is greater than that in softer rock formations.

According to the results of the numerical simulation, and considering certain safety coefficients, the reasonable sizes of the shaft-protecting coal pillar under different backfill ratio of 0%, 50%, 80%, and 90% are designed as 220 m, 176 m, 154 m, 132 m, respectively.

![Figure 5. Cont.](image_url)
Figure 5. The depth profiles of axial stress of the Baishan shafts at different backfill ratios. (a) The backfill ratio = 0% (#1–#8); (b) The backfill ratio = 50% (#9–#16); (c) The backfill ratio = 80% (#17–#24); (d) The backfill ratio = 90% (#25–#32).

4. Social and Economic Benefits of SBCM

4.1. Economic Benefits

At present, the backfill ratio usually can be controlled over 80% in the process of SBCM. According to the numerical simulation results, when the backfill ratio is 80% and 0%, the size of the shaft-protecting coal pillar is 154 m and 220 m, respectively, as shown in Figure 6.

When using SBCM technology to exploit RCPRIS under the condition of 80% backfill ratio, the coal production would be $1.92 \times 10^6$ t. The average selling price of coal from the Baishan Coal Mine is $88$ per ton and the average cost is $48$ per ton. So, the economic benefits would be $76.8$ million. When using caving method to exploit RCPRIS (backfill ratio = 0%, the size of the shaft protecting coal pillar = 220 m), the coal production would be $1.49 \times 10^6$ t and the economic benefits would be $59.6$ million.
between the rock formations. Furthermore, the axial stress of the shaft in hard rock formations is greater than that in softer rock formations.

According to the results of the numerical simulation, and considering certain safety coefficients, the reasonable sizes of the shaft-protecting coal pillar under different backfill ratio of 0%, 50%, 80%, and 90% are designed as 220 m, 176 m, 154 m, 132 m, respectively.

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Figure 6. Recoverable part of a coal pillar protecting shafts at Baishan mine liberated by SBCM.

Compared with caving method, using SBCM technology can get more economic benefit. The increment of coal production would be $17.2 million. The comparisons of the economic benefits are shown in Table 3.

Table 3. Comparison of the economic benefits.

| Exploitation Methods       | The Size of RCPRIS | Coal Height/m | The Size of the Shaft-Protecting Coal Pillar/m | Production/×10^6 t | Benefits/×10^6 Dollar |
|----------------------------|-------------------|---------------|-----------------------------------------------|-------------------|-----------------------|
| SBCM (Φ = 80%)             | 740 m × 720 m     | 3             | 154 m                                         | 1.92              | 76.8                  |
| Caving method (Φ = 0%)     | 740 m × 720 m     | 3             | 220 m                                         | 1.49              | 59.6                  |
| The increment              | -                 | -             | -                                             | 0.43              | 17.2                  |

4.2. Social and Environmental Benefits

Using SBCM technology to recycle RCPRIS can result in the following social and environmental benefits.

1. The RCPRIS of aged mines can be recovered efficiently, which will improve the recovery ratio of mine resources and relieve the problem of coal resource depletion of aged mines.

2. The service life of coal mines can be extended, which will earn valuable time for coal mine replacement or conversion. At the same time, the pressure of staff deployment can be relieved and the staff’s lives can be guaranteed, which is beneficial to the maintenance of coal mines and social stability.

3. By backfilling coal gangue into the goaf underground, the coal gangue stacked on the ground can be treated effectively, which can not only liberate many land resources but also reduce environmental pollution. This will promote the sustainability of the ecological environment.

5. Conclusions

1. An innovative exploitation method of using SBCM technology to recycle RCPRIS is proposed. By this exploitation method, the coal gangue on the ground is backfilled into the goaf, and the RCPRIS can be exploited under the premise of ensuring the safety of the shafts and buildings on the ground.

2. Based on the case of the Baishan Coal Mine, the numerical simulation method is adopted to study the reasonable size of the shaft-protecting coal pillar under different backfill ratio. When the size of the shaft-protecting coal pillar is the same, the disturbance to the shaft caused by exploitation
decreased with the increase of backfill ratio. The reasonable sizes of the shaft-protecting coal pillar decreased with the increase of backfill ratio.

(3) Based on the case of the Baishan Coal Mine, when using SBCM technology to exploit RCPRIS under the condition of 80% backfill ratio, compared with the caving method (backfill ratio = 0%), the increment of coal production would be $0.43 \times 106$ t and the growth of economic benefits would be $17.2$ million. The economic benefits are significant.

(4) Using SBCM technology to recycle RCPRIS can not only improve the recovery ratio of mine resources, which will relieve the problem of coal resource depletion of aged mine, but also can address the coal gangue on the ground and reduce environmental pollution. It is of great importance not only to promote the sustainability of aged coal mines but also to promote the sustainability of China’s social economy and ecological environment.

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