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ANALYSIS AND APPLICATION OF FILLING MINING TECHNOLOGY IN CHINA'S MINING AREA: A CASE STUDY OF YUXING COAL MINE

According to the requirements of green mine construction and the coordinated development of environmental protection regulations, the existing filling technologies in China are compared and analysed. Several types of technologies are discussed, including the dry filling technology for gangue, grouting and filling for separated strata zones in overburden, grouting and filling technology for caving gangue fissures, paste and paste-like filling, high-water and ultra-high-water filling, and continuous mining and continuous filling. Then, the characteristics of these individual technologies are analysed. Through the analysis and comparison of these technologies, considering the requirements of green mine construction and coordinated development of environmental protection regulations, it was found that continuous mining and continuous filling technology is a feasible mean for constructing green mines and protecting the environment. In this study, the application of continuous mining and continuous filling technology in the Yuxing coal mine is introduced. Results show that surface subsidence was less than 80 mm, and the recovery rate of the working face reached 95%. This indicates that continuous mining and continuous filling technology can solve the problems of surface subsidence, environmental damage, and coal resource waste. Finally, the development prospects of continuous mining and continuous filling technology are proposed, providing theoretical and technical support for similar mining.

Keywords: Coal Mine Filling Mining, Environmental Protection, Technology of Surface Subsidence Control, Engineering Application

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1. Problems in green mines construction

Green mines are a new initiative for building ecologically conscious civilizations. The premise of green mine construction is to operate the mine according to the law, and its primary function is to protect the environment and encourage the harmonious development of mining areas. Effective management coupled with scientific and technological innovation has enhanced the construction of green mines [1-3]. Currently, there are some issues facing the construction of green mines in China:

(1) Stricter requirements on the discharge of pollutants from factories and mines were put forward in China. With continuous improvements in requirements, the treatment of pollutants in coal enterprises becomes more pressing. This restricts the development of coal enterprises and is not conducive to the construction of green mines.
(2) Current coal seam mining methods lead to surface water losses, which affect regional hydrogeological conditions and the growth of regional vegetation. According to the principle of "who destroys, who governs" in China, coal mining enterprises will face severe land reclamation problems.
(3) Solving the issue of pressed coal under buildings, railways, and water bodies that cannot be addressed simply by demolition. To meet the needs of sustainable development and to ensure the safety of surface buildings, it is imperative to adopt effective technology to maximize the mining of coal under buildings.
(4) Currently, protective coal pillars are reserved for buildings and tunnels. These coal pillars have drastically effected the normal arrangement of the working face and production continuity and has rendered a large number of coal resources unable to be exploited and utilized.

Therefore, there are many issues in the process of green mine construction for coal mining enterprises. These issues include waste disposal in factories and mines, large-scale subsidence, the destruction of mined-out areas, pressed coal under buildings, railways, and water bodies, and the waste of resources. With the improvement of national requirements for environmental protection and emission regulation enterprises, greater pressure will be introduced to the operation and production of green mines.

2. Overview of filling methods

Currently, there are many filling coal mining technologies, including dry filling technology for gangue, grouting and filling for separated strata zones in overburden, grouting and filling technology for caving gangue fissures, paste and paste-like filling, high-water and ultra-high-water filling, and continuous mining and continuous filling [4,5].

2.1. Dry filling technology for gangue

The dry filling technology for gangue mainly includes the following four types: self-sliding filling, simple mechanical filling, wind filling, and artificial gangue belt [6]. Wind filling for gangue has stringent requirements for filling systems, equipment, and the filling materials [7,8]. The application scope is narrow. Studies on coal gangue filling in mined-out areas were carried out abroad in the 1980s [7-9]. In the 1960s and 1970s, dry filling of gangue was tested in China. Results of these studies showed that the surface subsidence coefficient of gangue filling mining is approximately 0.4-0.5 [10,11]. Previous engineering practices of dry filling of gangue showed that the filling operation has a significant impact on coal mining production due to the poor filling machinery and lack of theoretical guidance. As a result, gangue fill mining has not been widely developed [12,13]. However, dry filling of gangue has many advantages, such as wide material sources and lower mining costs. Therefore, many scholars have begun to increase the research on gangue filling mining methods, rock pressure and strata control theory, and gangue filling equipment [14]. The schematic diagram of this technology is as follows (Fig. 1).

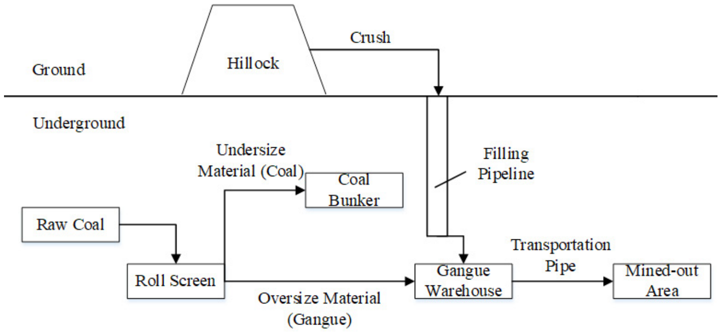

Fig. 1. Schematic diagram of dry filling technology for gangue
(The main filling material of this technology is coal gangue, which comes from ground hillock and underground raw coal)

2.2. Grouting and filling for separated strata zones in overburden

The technology of grouting and filling for separated strata zones in overburden is a new mining technology for reducing subsidence by grouting and filling in coal mines based on the movement laws of the strata. This technology uses the space formed in the process of overburden subsidence and cracking after coal mining combined with the use of a high-pressure grouting pump to inject filling materials into the spaces created by drilling. This method can support the upper separated strata and reduce future bending and subsidence of the strata to slow down the surface subsidence [15-17]. The technology of grouting and filling the separated strata zones in overburden was first developed in Poland in the early 1980s [18]. It was adopted in China in the late 1980s [19]. Since the success of the Fushun Mining Bureau's experiment using this technology to reduce surface subsidence, this technology has attracted the attention of experts and technicians in China's coal industry [20-22]. This technology has been tested in the Xuzhuang coal mine, Huafeng coal mine, Dongtan coal mine, and the Tangshan coal mine and has achieved good results [23-24]. The schematic diagram of this technology is shown in Fig. 2(a).

2.3. Grouting and filling technology for caving gangue fissures

Grouting and filling technology for caving gangue fissures reduces surface subsidence. This method entails injecting grout into the gap between caving gangue in the mined-out area, filling it and reinforcing caving rock to support the overlying strata [25,26]. According to different mining approaches, the grouting and filling technology for caving gangue fissures can be divided into grouting and filling in the caving zone of longwall mining, grouting and filling in the room-column caving zone, and grouting and filling in the caving zone of strip mining. Grouting and filling in the caving zone of longwall mining was mostly used in Germany and Poland [27,28]. In Germany, a new tailpipe filling technology was adopted in a fully mechanized mining face with longwall mining. The tailpipe was arranged in the mined-out area 18 m behind the working face. The roof caving here was not compacted, and the high concentration slurry filling material was injected into the whole hole [27]. In Poland, slurry with a 30% concentration of fly ash, tailings, a small amount of cement, and industrial waste brine was used to reinforce the caving zone of longwall stratified mining [28]. Grouting and filling in room-column caving zones is mainly used in the United States and Canada [27]. The Carlisle coal mine in Indiana, USA, has an average buried depth of 90 m and mining height of 2 m. Grouting and filling in a room-column caving zone was adopted here, and the coal recovery rate is 68-75% [27]. The schematic diagram of this technology is shown in Fig. 2(v).

2.4. Paste and paste-like filling

Paste and paste-like filling technology processes coal gangue, fly ash, slag, poor soil, municipal solid waste, and other wastes near the coal mine into paste slurry without critical velocity and ground dehydration. It is then transported to the underground filling mined-out area by a filling pump or by gravity through the pipeline to control the damage and deformation of the overlying strata caused by mining. This method can increases coal mining safety under buildings, can fully recover coal resources, and can protect the ecological environment of the mining area [29-32]. Paste filling technology is the fourth generation of filling technology first developed in the Grende lead-zinc mine in Germany in 1979 [33]. In 1991, the German Mining & Metallurgical Technology Company applied paste filling technology to coal mines for the first time. The test site was the Walsam coal mine, where the mining depth of the working face was 1000 m and the thickness of the coal seam was 1.5 m. The filling materials were gangue, fly ash, and broken rock powder with a particle size less than 5 mm and a mass concentration up to 76-84% [34]. The schematic diagram of this technology is shown in Fig. 2(c).

2.5. High-water and ultra-high-water filling

To solve the issue of filling material sources, high-water and ultra-high-water filling technology was proposed in China [35-37]. Research on high water content materials can be traced back to roadside pumping and filling technology used in Britain in the early 1980s [38]. A type of mixed cement binder called "Aquapak" was developed by the British Coal Research Institute (MRDE) [38,39]. Research on high-water materials was first carried out in China in the mid-1980s [40,41]. High water material is a new material with a water to cement ratio of 2.0-4.0. It is composed of two components, A and B, and the slurry is prepared by adding water. After mixing, the two kinds of slurry can solidify within 30 minutes. The compressive strength of the formed solid develops rapidly. The strength of the 2-hour compressive strength can reach 1.0-2.5 MPa, and the final strength can reach 5.0-6.0 MPa To further reduce the number of materials, ultrahigh water materials have appeared in recent years, with water contents up to 97% [42]. The schematic diagram of this technology is shown in Fig. 2(d).

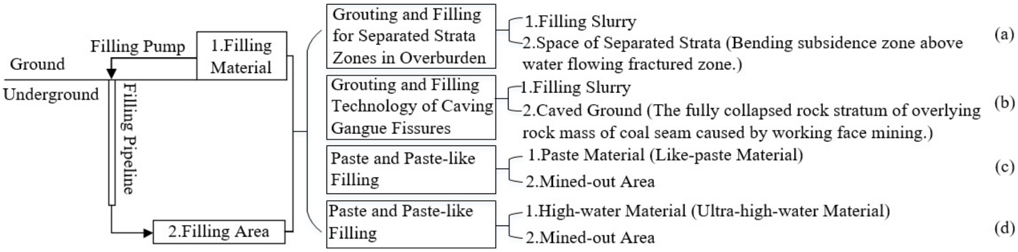

Fig. 2. The filling technology schematic diagram (a. Grouting and Filling for Separated Strata Zones in Overburden/b. Grouting and filling technology for caving gangue fissures/c. Paste and Paste-like Filling/d. High-water and Ultra-high-water Filling)

2.6. Continuous mining and continuous filling

Continuous mining and continuous filling technology is a new filling technology. The core technology of this filling technique is full potential energy paste-like filling. The filling materials are mainly coal gangue, fly ash, and other wastes discharged from factories and mines. Underground continuous mining and continuous filling mining technology is composed of a coal mining system and filling system. The coal mining and filling systems are two independent systems. The coal mining system includes the mining branch roadway and coal transportation, while the filling system includes the filling and filling material transportation of the branch roadway after mining. The two systems have a clear division of labour and no influence on each other. Also, parallel operation can improve the efficiency of coal mining and filling thereby achieving the purposes of "continuous mining and continuous filling", "filling to protect mining", and "filling to enhance mining" [43]. The schematic diagram of this technology is as follows (Fig. 3).

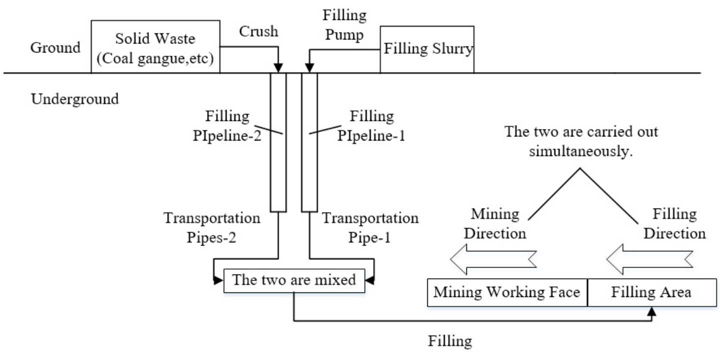

Fig. 3. Schematic diagram of continuous mining and continuous filling technology (Coal mining and filling are separated, and coal mining and filling are carried out simultaneously. The filling materials are discharged into the underground separately, and the underground mixture is filled into the mined-out area)

3. Filling mode selection

3.1. Characteristics of various filling methods

The main purpose of crushing gangue throw filling, mechanized gangue filling, and low-pressure wind pipe filling is to treat gangue, yet the overall control effect of ground subsidence is poor. There are some problems in paste and paste-like filling, such as large initial equipment investment, complex filling systems, high technical requirements, especially low filling efficiency, low annual output, and high filling cost. High-water and ultra-high-water filling mainly uses high water materials as fill. It also cannot deal with waste materials such as gangue and fly ash, and the long-term stability of high-water materials needs to be verified. Continuous mining and continuous filling technology can reduce the waste discharged from factories and mines into the mined-out area, not only protecting the environment but also mining coal pillars [44]. The specific characteristics of filling mining technology and the effect of reducing settlement are shown in Table 1.

TABLE 1

Characteristics of various filling methods and settlement reduction effects [10,45-48]

Filling mode	Filling rate	Subsidence coefficient	Advantages	Disadvantages	Applicable conditions
Grouting and filling for separated strata zones in overburden	0.3-0.5	0.5-0.6	Low cost, simple operation	It is difficult to predict the location and size of the separation layer, and the settlement reduction is not ideal.	Thin and medium thick coal seam
Dry filling technology for gangue	0.4-0.6	0.5-0.7	The system is simple, convenient for large area continuous filling and high mechanization	The construction process is complex, and the process time is affected by many factors.	Thin coal seam
Paste and paste-like filling	0.8-0.9	0.1-0.2	It has a wide range of application and remarkable effect of reducing sedimentation	The transportation concentration is limited, segregation and stratification are serious, pipeline wear is serious, and the cost is high.	Medium thick coal seam
High-water and ultra-high-water filling	0.8-0.9	0.3-0.5	The filling connection is better, the labour intensity is reduced, and the production efficiency is high	Affected by geological conditions, the cost is high.	Thin coal seam
Continuous mining and continuous filling	0.95-0.99	0.01-0.1	The system is simple, the filling connection is better, the mining and filling separation, the filling efficiency is high, and the effect of reducing subsidence is remarkable	At the stage of enhancement and trial, experienced construction team is required to organize construction.	Medium thick coal seam

3.2. Requirements for filling mode selection under the background of green mine

To fulfil the requirements of the Chinese government on coal mining operations, the primary task for coal mining enterprises is to rapidly build green mines. These requirements were put forward for the construction of green mines due to the need for comprehensive utilization of resources, technological innovation, energy conservation and emission reduction, and environmental protection. Therefore, the primary task is to select a reasonable filling method suitable for green mine construction. To select a suitable filling method, the following requirements should be met:

(1) The waste discharged from factories and mines should be backfilled in the mined-out area to address the issues of pollution from factories, mines and the treatment of subsidence areas.
(2) It is necessary to minimize the damage to the natural environment and create harmony between the development and utilization of mineral resources and the natural ecological environment. Resources will be recycled, land will be saved, and environmental destruction will be stopped at the source.
(3) Some coal pillars and stagnant coal resources should be mined out to avoid the waste of resources.

In summary, the selection of the filling mining method in Chinese coal mining enterprises is a complex process. It is necessary to consider different mining methods under different circumstances. It is also necessary to meet the requirements of green mine construction and fully consider the economic benefits of coal mining enterprises.

Compared with the characteristics of the abovementioned filling mining methods, and regardless of the filling rate or subsidence coefficient, continuous mining and continuous filling mining are obviously better than other filling mining methods. A high filling rate and small subsidence coefficient can better address the issues of building destruction around the coal mining face, retention of coal pillars, and the waste of resources. Therefore, for the mining of medium thick coal seams, continuous mining and continuous filling mining are superior to other fill mining methods.

4. Engineering practice of continuous mining and continuous filling

4.1. Engineering background

The Yuxing coal mine in Inner Mongolia is located in Etuoke Banner, Inner Mongolia Autonomous Region. At present, 16 coal seams with a mining thickness of approximately 7.0 m and 9 coal seams with a mining thickness of 5.0 m are being mined. The dip angle of the coal seams is approximately 10°, and the average burial depth is 260 m. Most of the recoverable reserves in the mine area are under buildings. The surface subsidence control level is high, and it is difficult to move. This maximizes the mining of coal resources and ensures that surface buildings are not damaged by mining. The Yuxing coal mine innovatively proposed the full negative pressure continuous mining and green fill mining method. This method combines the characteristics of full negative pressure ventilation in long wall mining, low investment and high efficiency in short wall mining equipment, and fill mining to control surface subsidence. The parallel operation of mining and filling in a thick coal seam working face was realized, the bottleneck of large-scale filling mining was broken, and the production efficiency was greatly improved. Compared to the efficiency of a fully mechanized working face, a major technical breakthrough of mine transformation was completed.

4.2. Mining and filling of the working face

The long wall working face is arranged on one wing of the mining area, and the whole working face is formed by the air inlet, return, and return air combined roadways. Full negative pressure ventilation is realized through the special design of the gateway connecting the roadway and adjusting the air door. A local fan is used to supply air when the upper layer of the branch roadway is mined, negative pressure ventilation is used when the lower layer is constructed, and an air window is used to control the air at the upper outlet of the branch roadway to ensure the ventilation of return air from the combined roadway. The layout of the working face is shown in Fig. 4.

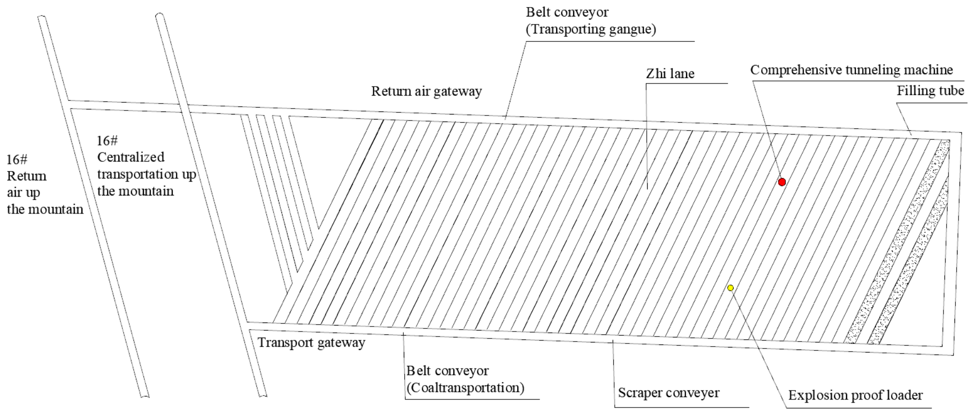

Fig. 4. Working face layout for continuous mining and continuous filling technology

The working face is composed of several roadways and coal pillars (roadway width is 5 m), and the roadways and coal pillars are arranged at intervals of 5 m, forming a layout with odd numbered roadways (1, 3, 5, 7…) and even numbered roadways (2, 4, 6, 8…). A continuous mining machine is used for coal mining, and a trackless rubber-tyred vehicle is used for transportation. The working face is first stratified by the odd numbered roadways from inside to outside, the roof and two sides are supported, and then the lower stratified material is mined. Each branch of the roadway is filled immediately after mining, and the cementation of the filling body is used to create the secondary permanent support of the roof, which creates conditions for coal pillar mining. After the subsections of the branch roadway are mined successively, the filling of the branch roadway also ends. With continuous mining, after a certain time interval, the solidification strength of the filling body has fully met the requirements. Then, the even coal pillar roadway was mined from the inside to the outside, and the continuous mined areas are also continuously filled. The upper and lower troughs of the working face are concentrated on undercover mining and filling after the mining of the working face and adjacent working face, where 100% equal volume replacement is realized. A single pillar is used as temporary support in continuous mining and continuous filling of the working face, and the parallel operation of excavation and support is realized, which ensures the success of continuous mining.

4.3. Filling effect

When the working face is filled from top to bottom and then from bottom to top, the secondary mining coal pillar roadway is fully filled, and there is no gap between the top, bottom, left and right. There is no pressure appearance on the roof of the roadway, and the filling effect of the two sides is good, especially after the roadway is covered (the maximum depth is 7.0 m). Then, the filling body of the two sides is complete, and there is no spalling. The results of laboratory compressive strength results are shown in Table 2.

TABLE 2

Summary of uniaxial test results of laboratory backfill

Number	Diameter/mm	Height/mm	Mass/g	Uniaxial compressive strength/MPa	Elastic modulus /MPa	Poisson's ratio
5# 10 m	49.01	100.50	276	3.6	990.516	0.029
5# 30 m	49.30	99.58	294	4.8	1845.846	0.022
5# 60 m	49.50	100.46	312	6.5	2191.909	0.020
9# 10 m	49.34	82.78	251	5.4	1339.332	0.028
9# 30 m	49.40	99.40	276	4.6	1359.513	0.028
9# 60 m	48.80	99.48	268	3.5	1380.307	0.021
Average	49.225	97.03	279	4.7	1517.90	0.023

The fill body is complete and has no deformation, indicating that the overall filling effect is good, especially due to its cementation, excellent shear strength, and the comprehensive supporting effect on the roof, which is superior to that of the coal body. The field filling effect is shown in Figure 5.

Monitoring points were set up on the surface during the mining of the 11601-filling working face, as shown in Fig. 6. Limited by the terrain, the observation line is not arranged along the

Fig. 5. Site drawing of continuous mining and continuous filling

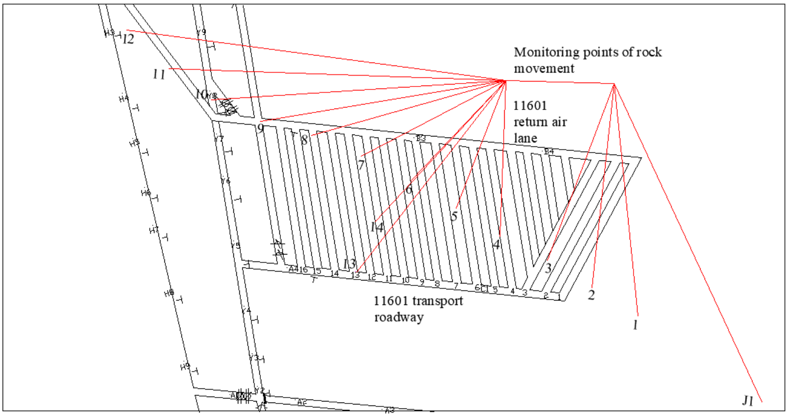

Fig. 6. Layout of ground monitoring points for the 11601-filling face

main section of the working face, but along the route above the working face. In the later stage, it was processed by fitting. This measurement is carried out by Gps and leveling instrument of Trimble. A total of 15 observations were carried out. The accuracy of measurement can be ensured by observing the requirements according to «Coal mine measurement specification». Because continuous mining and continuous filling technology adopts the way of interval skip-mining of branch roadway, mining and filling do not interfere with each other and work parallelly. In the early stage of working face mining, the ground subsidence is small, and the interval time of the first six measurements is relatively long, about 40 days. In the middle and late stages of working face mining, the ground subsidence increases, and the interval between two measurements is shortened to about 20 days. The surface subsidence curve is shown in Fig. 7, and the surface

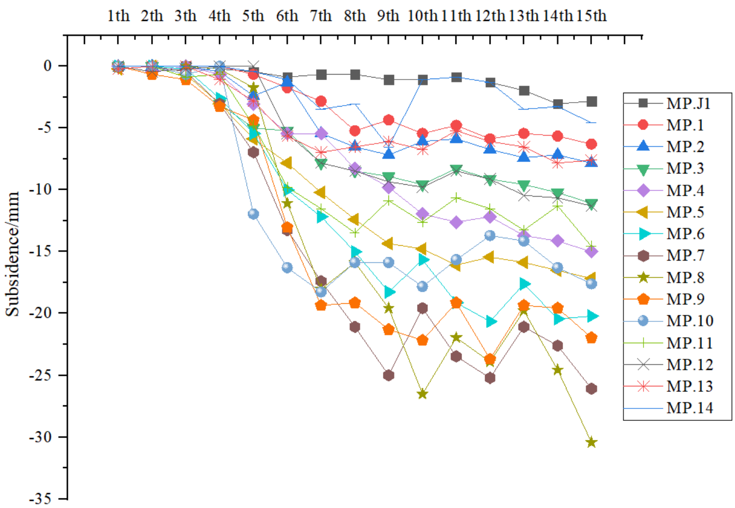

Fig. 7. Subsidence of ground monitoring points (MP. = Monitoring Point)

subsidence was less than 40 mm. There was little change in the ground surface, and no new cracks were found in the buildings under the mining area. The field industrial test showed that the mining method had a significant control effect on surface deformation, which can ensure the stability of buildings on the surface.

4.4. Filling Benefits

The Yuxing coal mine carried out filling mining tests at working faces 11601~11604, and the recovery rate of the working face reached 95%. After calculation, the direct cost of filling is 5.2 USD/T. See Table 3 for comparison with other filling technologies.

TABLE 3

Filling process filling cost comparison table

Contrast content / Filling method	Production capacity (10000 t/a)	System investment (Million Dollars)	Filling cost (USD/T)
Dry filling technology for gangue	50~70	7.7~10.8	4.6~9.2
Paste paste-like filling	40~50	7.7~10.8	12.3~18.5
Continuous mining and continuous filling	90~120	1.2~1.6	3.1~6.1

4.5. Comprehensive analysis

After improvements in continuous mining and continuous filling technology in the Yuxing coal mine, satisfactory results have been achieved.

(1) In a continuous mining face, a single fully mechanized excavating machine can achieve a daily advance of 30 m for the upper layer and 50 m for the lower layer. The monthly output reaches 23000 t to 30000 t, and the monthly output of two fully mechanized excavators is 50000 T. Currently, it is the highest level of filling mining technology.

(2) The separate transportation of slurry and gangue solves the issue of slurry pipeline blockage.

(3) The working face is filled with concrete, and the strength of the filling body is 80% (4.66 MPa) of the final strength one month later, with the control effect on surface settlement being superior to other current filling methods.

(4) A way that the coal pillar can be mined after the working face is filled was designed, and the enrichment rate of the working face was 99%.

(5) The filling speed was greater than the mining speed, and the problem of filling restricting mining was solved innovatively.

(6) The recovery rate of the mine with continuous mining and continuous filling mining technology can reach 90%, which is 10% higher than that of mines with fully mechanized coal caving technology. The recovery rate of the continuous mining and filling of the working face reaches 95%, which is 9% higher than that of the fully mechanized caving working face.

It is both necessary and feasible to carry out continuous mining and continuous filling technology in the construction of green mines. The mature and reliable technology of continuous mining and continuous filling can solve the issues of waste disposal, large-area subsidence, and damage to mined-out areas currently faced by coal mining companies. This method can extract stagnant coal resources such as protective coal pillars of underground roadways and ground buildings, optimize the working face layout, and extend mine service lifespans. This technology has great promise in policy, technology, safety, and economic benefits.

5. Research direction and prospect of continuous mining and continuous filling technology

Continuous mining and continuous filling technology is a new, environmentally friendly, and safe filling mining technology. It is a new direction of coal mining in China. Continuous mining and continuous filling technology is in the early stages of popularization and use, so more in-depth research is needed.

(1) It is important to develop relevant construction equipment to improve the mechanization and construction efficiency of continuous mining and continuous filling technology.
(2) A scientific and systematic evaluation mechanism is needed to provide theoretical support for effective monitoring of these technologies.
(3) Under different geological conditions, it is necessary to select the appropriate coal mining enterprises for the test.

The successful development and application of continuous mining and continuous filling technology has significant implications. Especially for enhancing the waste disposal of China's coal mining enterprises, improving the recovery rate of mine resources, and encouraging green mine construction. Therefore, continuous mining and continuous filling technology is recommended as a future development direction for Chinese coal mining enterprises.

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