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RESEARCH ON APPLICATION OF STRIP BACKFILLING MINING TECHNOLOGY – A CASE STUDY

Strip backfilling mining technology is of great significance for eliminating coal gangue, improving coal recovery rate, harmonizing the development between resources and environment in diggings. This paper firstly analyzed the roof control mechanism, the deformation and failure mechanism and characteristics of the filling body through theoretical analysis. Then, through numerical simulation combined with the geological conditions on site, a gangue strip filling scheme was designed for the 61303 working face of the 13th layer of the rear group coal of the Wennan Coal Mine in Shandong Province, and the filling scheme of filling 50 m and leaving 25 m was determined. Finally, an on-site engineering test was carried out on the 61303 working face. Through the analysis of the measured data of "three quantities" after the filling test, it can be seen that the test has achieved a good engineering application effect and verified the rationality of the filling scheme design. It solves the coal gangue problem, improves the resource recovery rate, and provides a reference for other similar mines.

Keywords: coal gangue, strip backfilling mining, numerical simulation, scheme design, construction technology

1. Introduction

China is rich in coal resources, and its coal reserves and production rank among the highest in the world. However, all mines have different levels of low resource recovery rates and pollution of coal gangue on the ground, all of which seriously restrict sustainable development of mining areas [1-3]. Therefore, mineral resources must be developed and utilized while protecting the environment.

Although China's coal reserves and production are relatively large, but at the same time, various mining areas have different degrees of coal accumulation under buildings. A large amount

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of coal resources are sluggish and the resource recovery rates are low, which not only affect the development and utilization of resources by mining companies, but also increase the difficulty of development and shorten the service life of the mine

At the same time, coal gangue produced underground is piled on the ground, not only occupying a large amount of land resources and polluting the environment, but also causing great harm to human safety. The goaf is the largest space in the well. The use of coal gangue filling technology to directly dispose of coal gangue generated in the goaf is one of the most reasonable solutions [4,5]. Using the coal gangue to back the goaf can help prevent environmental pollution. The filled coal gangue can also act as a subsurface structural support for overburden, which reduces surface subsidence and protects surface construction. However, the current full filling mining still has shortcomings such as high cost, complicated process, and poor adaptability, which limit its large-scale application in mining companies [6-8]. Strip backfilling mining can help control overburden settlement and digest the coal gangue on the basis of cost reduction. Compared with full filling in the goaf, strip backfilling mining is more suitable for use in mines with suitable conditions [9,10].

The horizontal six mining area at –650 m in Wennan Coal Mine was taken as an example in this paper. We propose a coal gangue cemented strip backfilling mining method; the design, construction, and analysis of the coal gangue cemented strip backfilling are introduced. This research can not only realize the high-efficiency mining of coal under the building and mitigate the auxiliary lifting of the mine, but also can directly process the gangue produced in the mine, eliminating the harm caused by the accumulation of gangue on the human survival and living environment. It can realize the coordinated development of resources and the environment in the mining area, and build a green mine development mode in which man and nature are harmonious.

2. Analysis of control mechanism, deformation and failure characteristics of the strip filling roof

2.1. Introduction to strip filling

Strip backfilling mining is a new type of filling mining technology, which is based on room and pillar mining. After the coal seam is produced but before the roof of the working face collapses, the filling strips are alternately constructed along the advancing direction of the working face, that is, filling strips with a certain width are filled at intervals (Generally, if the unfilled area width (b) is less than the limiting step of the main roof rock beam fracture (L_0), then the strip is not filled). The load on the filling body and the roof itself are used to jointly bear the overburden load in the goaf [11-13], as shown in Fig. 1, where the arrow points along the direction in which the face advances. This method and strip mining have similarities in mechanical research. They both support the overlying roof through a support body of a certain width , and control the overlying key layer or the main roof rock layer not to break, so as to reduce the pressure of the working face and the sinking of the ground. The process is relatively simple, the working face does not need to be moved frequently, and the original normal mining conditions can be used for filling and mining.

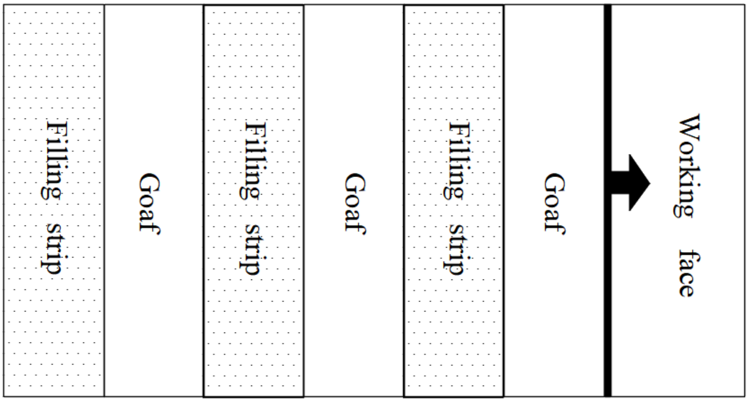


Fig. 1. Strip filling diagram

2.2. Mechanism of action of strip filling body and roof

2.2.1. Mechanism of the roof movement

After the coal seam is mined, the overlying rock layer will be destroyed and displaced. In the working face where the roof is managed by the total collapse method, when the working face advances a certain distance from the open cut, the immediate roof will begin to collapse after overhanging a certain span, and the softer immediate roof may fall at any time with the advance of the working face, and the roof collapses with mining. At this time, the hard basic roof is still exposed above the goaf as a plate-like structure due to its large fracture step. When the basic roof rock reaches its strength limit, fractures will be formed at both ends and the middle of the rock beam. That is, the so-called working face pressure.

Due to the particularity of the mining method, the characteristics of roof collapse and the mechanism of surface movement of strip backfilling mining are completely different from those of caving mining. Strip backfilling mining supports the roof through the filling body. The roof damage is less than that of full caving method, generally only causing cracking damage and no caulking damage. The bending of upper rock layer and the compression of filling body are dominant in strip backfilling mining. The full caving mining is mainly the collapse and fracture of the lower rock layer and the bending deformation of the upper rock layer. There are significant differences in movement characteristics of the two [14-17], as shown in Figs. 2 and 3.

In strip backfilling mining, as the self-opening cut of the working face advances, a certain width of cemented gangue strips are filled at intervals. Similar to strip mining, the overlying roof is supported by the filling strips. In the unfilled goaf, if the immediate roof is a soft rock, it will generally collapse with the mining as the working face advances. If the immediate roof rock is harder, its collapse is related to the width of the unfilled goaf. Generally, its width is greater than the collapse step of the immediate roof, and the immediate roof will collapse

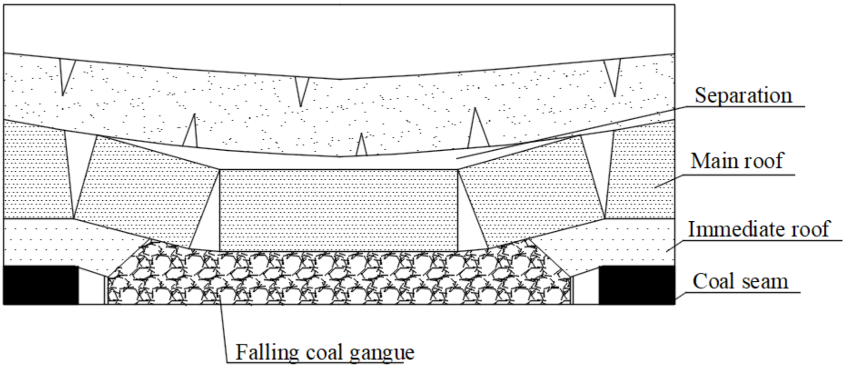
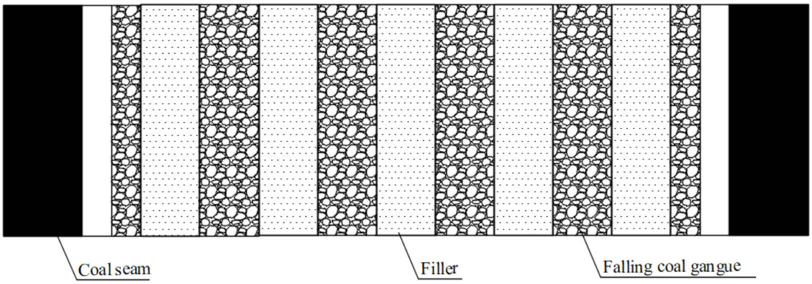
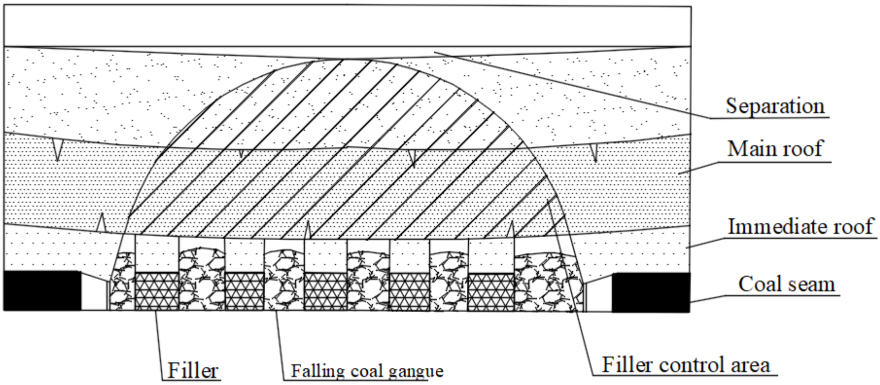


Fig. 2. Schematic diagram of all fallen mining roof



(a)Top view



(b) Sectional view

Fig. 3. Schematic diagram of the roof during strip filling

2.2.2. Mechanical mechanism of filling body to roof

The effect of filling body on the surrounding rock is mainly support, share pressure and prevent the deformation (or displacement) of the roof, while the improvement of the residual strength of the roof is secondary. For a large-area filling body, it also provides control of large-area ground pressure activities [18,19]. The action of the filling body on the roof is a process of support and pressure yielding, as shown in Fig. 4.

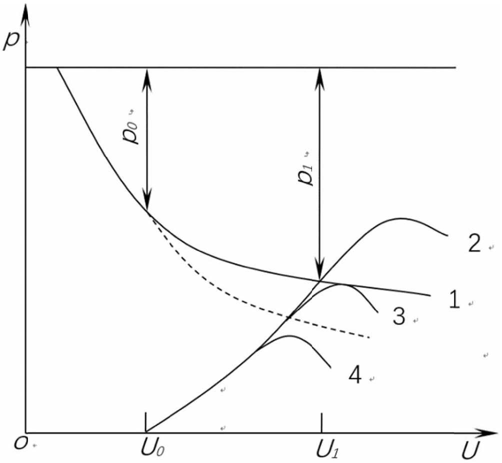


Fig. 4. Interaction between the filling body and the roof
1 – pressure-deformation curve of an overburdened roof; 2 – deformation curve of the filling body when the compressive strength is $\sigma > P_1$; 3 – deformation curve of the filling body when $\sigma = P_1$; 4 – deformation curve of the filling body when $\sigma < P_1$.

In Figure 4, U_0 is the displacement of the roof before filling and U_1 is the displacement generated by the filling body and the roof after filling. When $U = U_0$, a stress reduction zone is formed within a certain range of rock mass around the mining goaf (i.e., the unloading area), and the stress decreases by p_0. When the filling body can provide a sufficient supporting force, the pressure on the overburden decreases by p_1. When the uniaxial compressive strength $\sigma > p_1$, the filling body can provide sufficient passive supporting pressure p_1 to support the roof and form a joint, and the filling body has sufficient strength to remain stable. When the uniaxial compressive strength $\sigma < p_1$, the strength of the filling body is low. It is difficult to form a joint with the overburden, and the filling body is destroyed by pressure, leading to further deformation. When the uniaxial compressive strength of the filling body $\sigma = p_1$, the strength of the filling body is exactly equal to the force exerted by the overburden. The filling body is in the limit equilibrium state [20,21].

2.3. Analysis of strip filling body deformation and failure

Because the length of the filling body in the dip is much larger than the width of the strike, the filling body can be regarded as a plane strain state on a plane perpendicular to the long axis. Meanwhile, during the process of compressive deformation, the filling body is in a triaxial compression state due to the lateral restraining force of the immediate roof collapsed on both sides. Triaxial compression tests of the cemented backfilling samples show that the deformation and failure of strip filling body undergoes four stages after loading: I-elastic deformation, II-yield, III-plastic deformation, and IV-plastic failure [8,10,22]. The stress-strain curve of the coal gangue cemented strip filling sample under triaxial compression is shown in Fig. 5.

After the strip filling body is filled, the external stress is largest along the width direction of the filling body and gradually decreases toward the deep part as the working surface continues to advance [23,24]. Because the uniaxial compressive strength of the cemented backfill is very low, the outer filling body will quickly reach its strength limit and then rapidly break. The peak stress $\sigma_{\min}$ moves to the center of the filling body, forming the stress distribution state as shown in Fig. 6 [25]. Obviously, the area outside the peak point is an inelastic deformation zone, and the center is an elastic deformation zone. Regarding the equilibrium state of the cemented backfill, its behavior must also display: I-surface damage zone, II-plastic zone, III-yield zone, and IV-elastic center zone, as shown in Fig. 6.

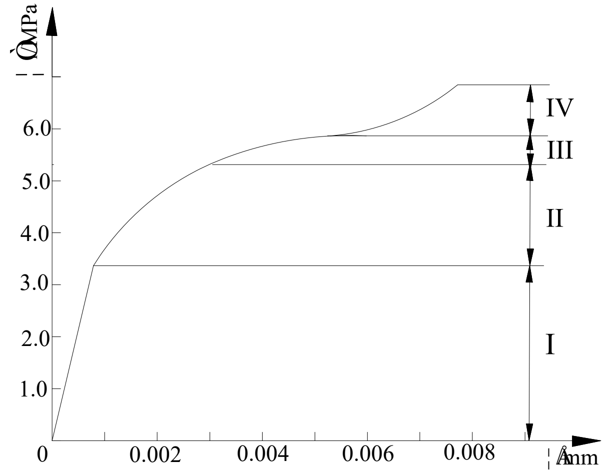


Fig. 5. Stress-strain curve of a coal gangue cemented strip filling sample under triaxial compression

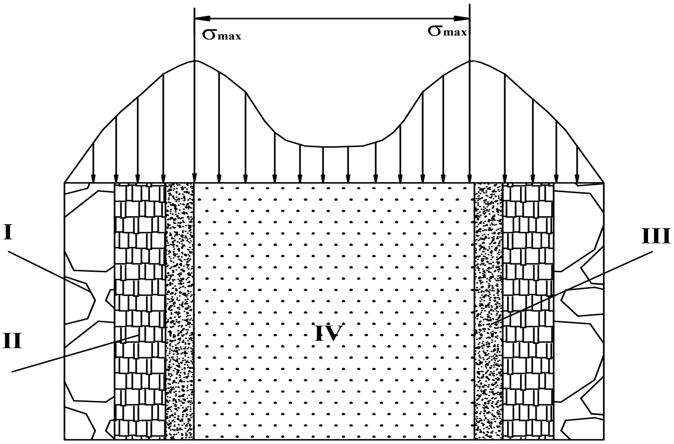


Fig. 6. Stress distribution of the cemented backfill

3. Technical application of coal gangue cemented strip filling body

An analysis of the control mechanism, deformation and failure of the strip filling roof shows that the stability of the roof filling strip is determined by many factors. The geological conditions of the coal mine are now used to design a filling scheme and on-site construction technology taking the 61303 working face of Wennan Coal Mine in Shandong as an example.

3.1. Overview

The 61303 working face, a dip working face in the Wennan Coal Mine, is located at the lowest part of the sixth mining area (–650 m). The working face is 1150 m long and the slope width is 180 m. The coal seam thickness in the working face is 1.62 m, and the average dip angle is 10°. It is a stable coal seam. The roof and floor of the coal seam are shown in Table 1. The average volume of solid coal gangue produced from the well is 144 m^3/d, the amount of loose coal gangue is 288 m^3/d, and the volume of goaf produced during normal production is approximately 291.6 m^3/d. A blasting machine and longwall backward mining are used to mine the 61303 filling working face. It is designed to use the gangue filling method to treat the goaf.

TABLE 1

Roof and floor conditions of coal seams

Roof and floor names	Rock name	Thickness (m)	Characteristic
Main roof	Siltstone	18.31	Dark gray, shell-like fracture, unidirectional compressive strength is 49 MPa.
Immediate roof	Four gray	6.62	Gray, compact and relatively pure, one-way compressive strength is 61.8 MPa.
Immediate floor	Mudstone	0.2	Gray, dense and hard, muddy cement, unidirectional compressive strength is 59.7 MPa.
Main floor	Middle sandstone	5.17	Dark gray, compact and brittle, unidirectional compressive strength is 32 MPa.

3.2. Strip filling scheme

3.2.1. Filling parameter design

According to rock beam theory [26], the limit collapse step of the main roof rock beam fracture in the 61303 working face is $L_0 = \sqrt{\frac{2m^2[\sigma_t]}{\left(m+\sum m_i\right)\gamma}} = 38.8\text{ m}$. Therefore, the width of the unfilled area is $b \leq 38.8$ m. Considering that the filling body has a plastic zone of a certain width due to the overburden load, the supporting capacity and effective support area are reduced. The width of the filling area is finally determined to be $b = 25$ m.

Stress is non-uniformly distributed along the width of the filling body due to the elastic deformation, yielding, plastic deformation, and plastic failure under triaxial compression. This indicates that the strip filling body is the same as the strip coal pillar. The overlying load creates a plastic zone and an elastic core zone. The width of the plastic zone should be determined by experiments in combination with on-site conditions [27,28]. FLAC3D numerical simulation software combined with the geological conditions of 61303 working face in sixth mining area of Wennan Coal Mine was used to determine the width and filling width of the plastic zone on both sides of the coal gangue cemented filling body.

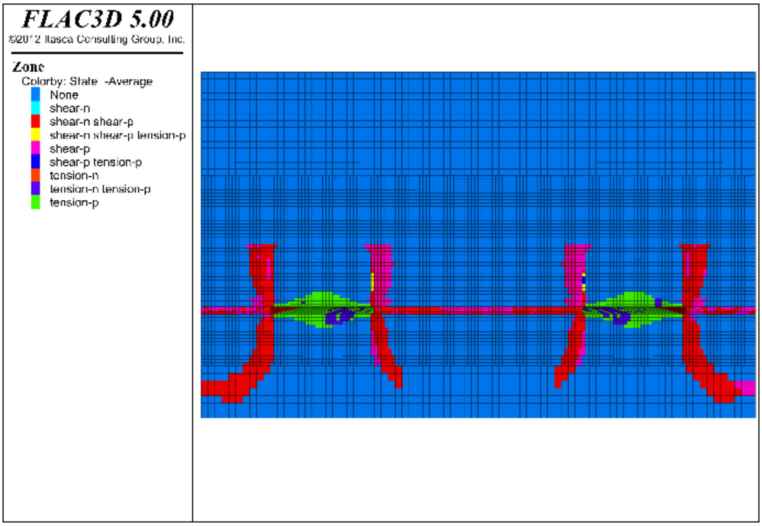
The simulated working face belongs to the near horizontal coal seam, so it was considered as a horizontal coal seam in the simulation. Meanwhile, in order to increase the calculation speed and ensure sufficient accuracy, the model considers a 200 m rock formation above and below the coal seam, and the rock mass above the upper boundary of the model was used as the stress boundary condition for the upper boundary of the model. Uniform load q is related to the lithology and buried depth of the overlying strata, i.e. $q = \sum \gamma g h$, where γ is the bulk density of the overburden, g is gravitational acceleration, and h is the thickness of the overburden with the value of 600 m. The x direction in the model spanned 500 m, and the length of the working surface was set to 180 m in the y direction and 200 m in the z direction. The model was constructed with a total of 59,800 units and 68,859 nodes. A total of six measuring points were arranged in the filling body and the upper top plate to monitor the maximum unbalanced force of the model and displacement and stress changes of the six measuring points.

By using FLAC3D numerical simulation software for simulation analysis, when the width of the unfilled area b is 25m, the width of the filling body is 30 m, 50 m and 70 m respectively, and the filling rate is 54.5%, 66.7% and 73.7% respectively. After fully considering the filling cost and maximizing the profit of coal mining companies, the scheme shown in Fig. 7 was determined to be the optimal solution. The filling rate is 66.7%, the filling area width is 50 m, and the plastic width ratio ranges from 27% to 30%.

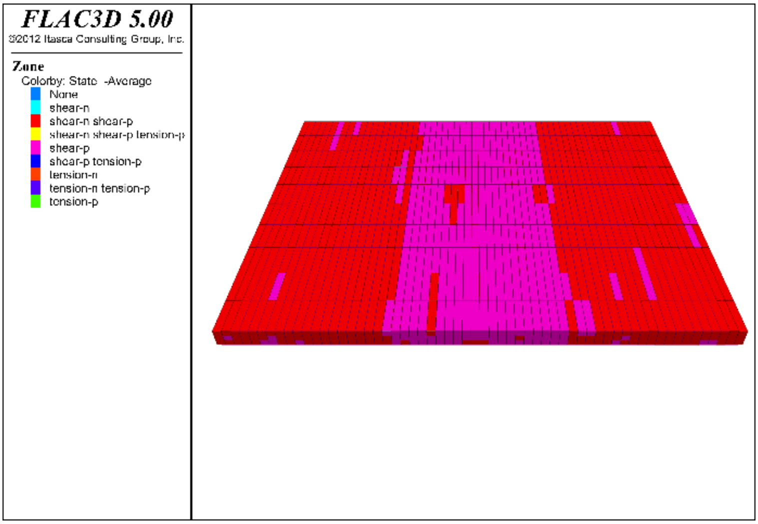
3.2.2. Filling body strength calculation

According to AH Wilson’s two-zone constraint theory and King’s effective region theory, the vertical stress in the goaf is proportional to the distance from the coal wall. When the distance reaches 0.3H, the vertical stress in the goaf is restored to the original load γH, as shown in Fig. 8 .

According to the previous analysis and calculation combined with the comprehensive histogram of the working face, there is a 3 m to 5 m thick sandstone-fine sandstone interbed above the 18.31 m thick main roof, and 0.37 m thick coal 12 and 11.46 m thick fine sandstone upward. According to King’s effective region theory and rock movement law, it can be seen that the sandstone-fine sandstone interbed and coal 12 above the main roof rock beam will settle with the settlement of the main roof. Because the thickness and hardness of the fine sandstone are large, it will not follow the settlement of the main roof. Therefore, the filling body only needs to bear the load of the main roof, sandstone-fine sandstone interbed and coal 12 after the immediate roof collapses. The vertical load is $\sigma_p = \gamma H$. The average bulk density of the load is 25 kN/m^3, and the total thickness H = 22.68 m, thus $\sigma_p = \gamma H = 0.57$ MPa. Consequently, the uniaxial compressive strength of the filling body must be greater than 0.57 MPa.



(a) Overall plastic deformation distribution



(b) Plastic deformation distribution of the filling body

Fig. 7. Plastic zone distribution map

3.2.3. Filling material ratio

The main components of cemented filling are coal gangue, cement, fly ash, and water, wherein the particle size of coal gangue, the grade and amount of cement, the amount of fly ash and the amount of water have a great influence on the quality and strength of the filling body.

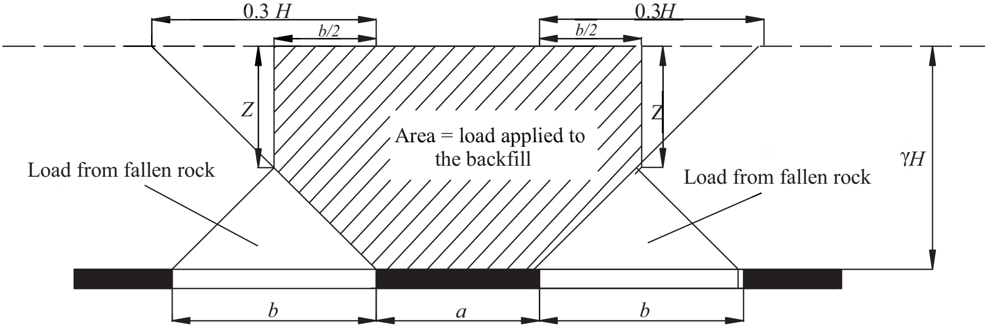


Fig. 8. Actual load bearing diagram of the goaf and backfill

The goal of coal gangue cemented filling is to minimize cost and maximize mechanical strength. The following basic principles must be followed when selecting the mixing ratio of the filling slurry: selecting reasonable filling materials, meeting the requirements of the conveying process, the lowest filling cost, the sample mixing ratio and preparation process, and the strength of filling body meeting the requirements of mining process.

The cemented filling is mixed with cement, fly ash and water to make cemented backfill after the particle size of crushed vermiculite waste is ≤30 mm. Through a uniaxial compressive strength test with different material ratios, the optimal proportion was determined to meet the requirements of filling strength and cost control. The various material proportions are shown in Table 2.

TABLE 2

Filling material proportions

Serial number	**Ash ratio**	**Ash to powder ratio**	**Filling material dose (kg)**				**Uniaxial compressive strength (MPa)**		
			water	**cement**	**fly ash**	**rubble**	**3 d**	**7 d**	**28 d**
1	1:4	7:1	200	100	700	400	0.49	1.16	2.36
2	1:5	2:1	75	100	200	500	1.06	3.69	4.22
3	1:6	4:1	125	100	400	600	0.86	1.99	3.16
4	1:7	6:1	175	100	600	700	0.49	1.48	2.96
5	1:8	8:1	225	100	800	800	0.34	1.08	2.46
6	1:9	3:1	100	100	300	900	0.43	1.60	3.11
7	1:10	5:1	150	100	500	1000	0.47	1.19	2.52

From calculating the filling body strength, it can be known that $\sigma_1 = 0.57$ MPa. A comparison of the uniaxial compressive strength shows that the scheme 2 and 3 have the lowest uniaxial compressive strength greater than 0.57 MPa. The safety factor in scheme 2 is $f = 1.06/0.57 = 1.86$, while the safety factor in scheme 3 is $f = 0.86/0.46 = 1.5$. Both schemes meet the strength requirements of the filling body. Considering the filling cost, scheme 3 consumes more coal gangue and fly ash for the same quality cement. Therefore, scheme 3 is finally determined, and the proportion of water, cement, fly ash, and coal gangue waste in scheme 3 is 1.25:1:4:6.

3.3. On-site construction process

3.3.1. Working face layout

Arrange a 13-layer coal auxiliary coal haulage dip at 365 m west of coal haulage rise in No. 6 Mining, and arrange 13-layer coal auxiliary material transporting dip at 20 m east of auxiliary coal haulage dip, and arrange a 13-layer coal auxiliary material transporting dip at 20 m east of auxiliary material transporting dip. Drain the gangue in an oblique alley. The 61303 middle parking lot is arranged at the position of the protection coal pillar line of the –650 m west main road, and the lower parking lot is arranged under the auxiliary material transporting dip. Arrange sump and pump house on the west side of 61303 Xiaxiang and north of auxiliary dip.

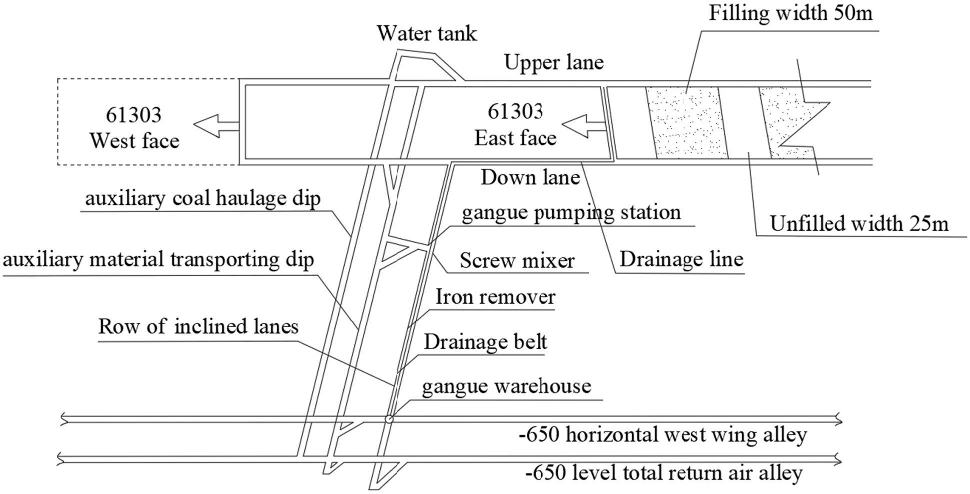


Fig. 9. Road layout of the working face

3.3.2. Construction process

The filling method is primarily based on “fill four-sevenths” meaning that if the goaf is divided into seven equal parts, four of them are filled. When the working surface meets the structure or the roof breaks, either the “fill three-sixths” or “fill two-fifths” filling method were used. When the working face goaf is filled with cemented coal gangue, the filling pipe is laid in the neutral of the second and third rows of pillars [29,30]. The specific filling process includes filling pipeline inspection, hanging bamboo raft plastic ribbon, returning the column, barrier gangue wall, filling, shrinking the filling pipe, and installing the filling pipe.

4. Engineering application effect analysis

In order to understand the roof pressure appearance and movement law of the working face after gangue filling, and to provide reasonable technical parameters for the gangue filling face under other similar conditions, the rock filling compaction measurement study was carried out on the filling face during the filling process. The observation lasted 43 days. The real data on site is obtained, and by comparing the appearance law of mine pressure on the working face of the roof with all caving method management, a reasonable evaluation of the filling effect of the rock-grinding strip filling method is carried out.

Fig. 10 shows motion of the top and bottom plates, pillar load, and live column shrinkage for the 61303 filling working surface during filling. Due to the huge amount of data, only the field data for the pillar load are listed, as shown in Table 3. The approach of the top and bottom plates and column shrinkage were directly derived from the field data.

One can see from Fig. 10 that the data are similar for all three quantities when the roof is pressed several times, indicating that there is no obvious initial pressure, and the cycle pressure step ranges from 13 m to 15 m (14 m average). The dynamic load coefficient is small when pressure is applied and the normal mine pressure is not strong, which indicates that the filling

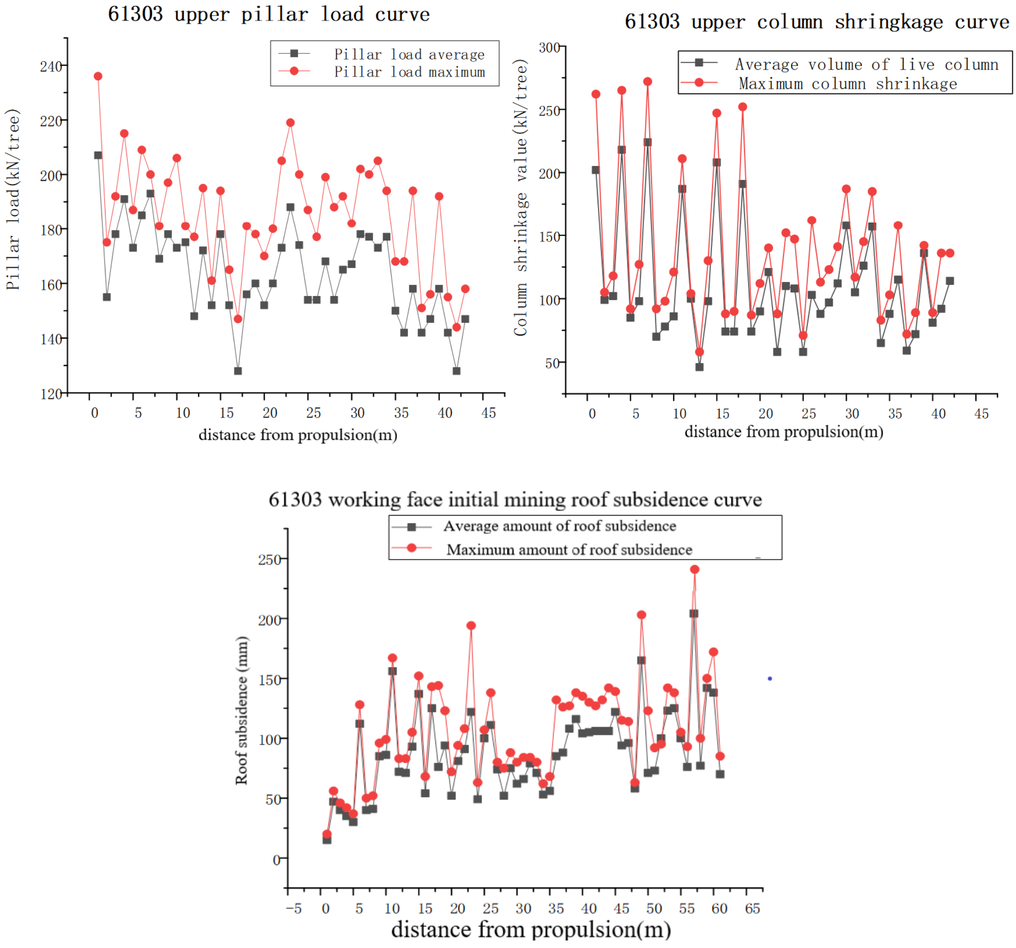


Fig. 10. Three quantities data graph

TABLE 3

Pillar load measured data

A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
B	207	155	178	191	173	185	193	169	178	173	175	148	172	152	178	152	128	156	160	152	160	173	188	174	154	154	168	154	165	167	178	177	173	177	150	142	158	142	147	158	142	128	147
C	236	175	192	215	187	209	200	181	197	206	181	177	195	161	194	165	147	181	178	170	180	205	219	200	187	177	199	188	192	182	202	200	205	194	168	168	194	151	156	192	155	144	158

A – Propulsion distance (m); B – Pillar load average/kN/tree; C – Pillar load maximum/kN/tree

body effectively controls the motion of the overlying roof beam and provides strong support. Meanwhile, filling with waste rock increases the recovery rate of coal resources and prolongs the service life of the mine. This solves the problem that underground coal gangues are raised to the ground and occupy a large amount of cultivated land, eliminates self-ignition and acid rain hazards caused by the stacking of coal gangues, and improves the ecological environment around the coal mine. Pumping the gangue cement fill into the test area reduces annual expenditures by 56.695 million yuan, providing significant economic and social benefits.

5. Conclusion

The coal gangue cement strip filling body supports the roof of the goaf, which can effectively control surface subsidence. The filling body experiences elastic deformation, yield, plastic deformation, and finally plastic failure due to pressure from the overburden. The action of the filling body on the overburden is a process of support and pressure. When the filling body experiences plastic deformation at full width and the “elastic core zone” disappears, the filling body will be unstable and destroyed.

A numerical model describing the geological conditions of the 61303 working face of the 13th layer of the rear group coal of the Wennan Coal Mine, was used to determine the filling parameters for the test working face. The filling body width $a = 50$ m, the unfilled area width was found be $b = 25$ m. A filling test was on the working face of the 61303 working face of the 13th layer of the rear group coal was conducted. No obvious compression can be seen after filling the working face, which indicates the coal gangue filling body in the goaf provides sufficient support and effectively controls the motion of the overlying roof.

The strip backfilling mining technology is simple and highly mechanized, which reduces the post staffs and the links of lifting and transporting the gangue to the ground, solves the problem of large amount of cultivated land occupied by gangue hill, improves the ecological environment of the coal mine, controls the surface deformation, improves the recovery rate of coal resources, and reduces the potential safety hazards. The annual revenue and expenditure can be increased by 56.695 million RMB with significant economic and social benefits.

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