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REVIEW ARTICLE

# Development overview of paste backfill technology in China's coal mines: a review

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## Abstract
After years of development, paste backfill technology has become an important part of China's green safety mine construction and coal green mining technology system in the new era. In this paper, the research status of paste backfill technology in China's coal mines is expounded from the aspects of paste backfill materials, strata control theory, and paste backfill technological process. Based on the statistics of the distribution number of coal mines adopting paste backfill technology, several typical paste backfill mines are listed, and the parameters of backfill panel, geological conditions, and paste backfill effect are analyzed, the general conditions of applying paste backfill technology in coal mines are summarized. Finally, some problems in the application of paste backfill technology are pointed out, and the future development of backfill mining is prospected from the research and development of backfill materials, deep underground backfill mining, intelligent paste backfill, and other aspects. This paper provides a reference for a comprehensive and in-depth understanding of the current development status of paste backfill technology in China.

**Keywords** Green mines · Coal mining · Paste backfill technology · Current status

## Introduction

For a long time, coal has been the main energy source in China, which has occupied the main position in China's primary energy output and consumption, and has had an important impact on China's economic development and social stability (Fang et al. 2018; Song et al. 2016). China's energy occurrence is characterized by poor oil, less gas, and rich coal. And coal, as petrochemical energy with the longest development history and mature mining technology, will continue to play an important role in China's economy, society, and environment for a long time to come (Hao et al. 2016; Cao et al. 2016; Betz et al. 2015). Figure 1 shows the proportion of China's primary energy output and consumption in 2020, which shows the importance of coal to China's development.

Although coal has made a great contribution to China's economic and social development, the traditional mining methods of coal resources have caused many problems (Ahern and Hendryx 2012; Adibee et al. 2013; Bernhardt et al. 2012; Chen et al. 2014; Hussain et al. 2016; Kurth et al. 2015; Song and Wang. 2019), such as the discharge and accumulation of solid waste, water-soil erosion, air pollution, ground surface subsidence, and coal or rock dynamic disasters, as shown in Fig. 2.

In addition, after long-term, high-intensity, and large-scale mining activities in central and eastern China, the coal resources with superior burial conditions and good quality have been continuously reduced. Therefore, coal enterprises in central and eastern China are not only faced with solid waste accumulation, surface subsidence, and other problems,

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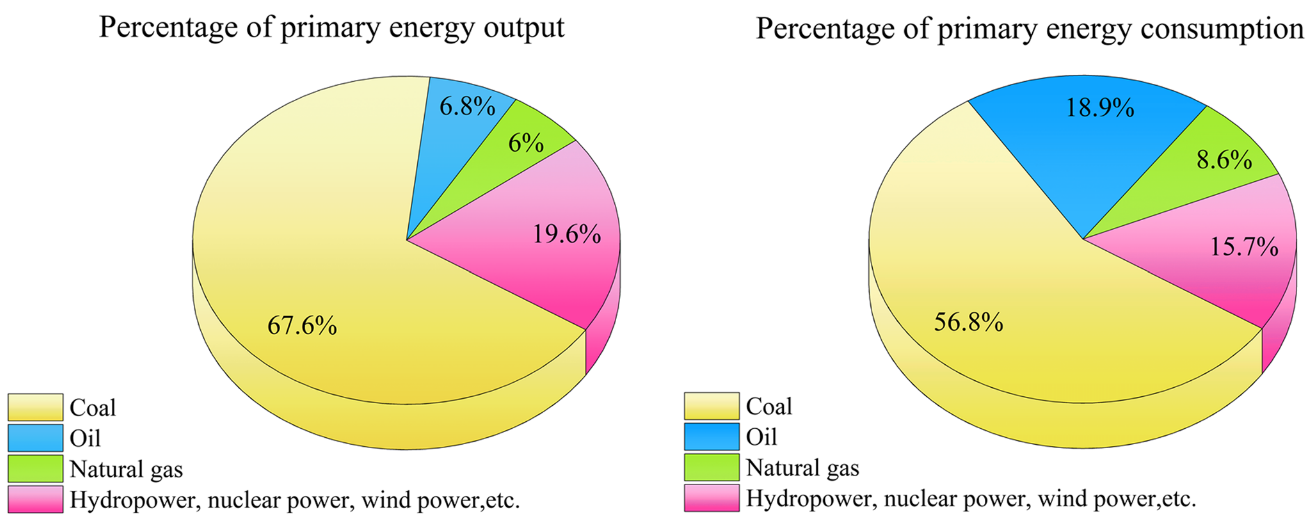



**Fig. 1** The proportion of China's primary energy output and consumption in 2020


**Fig. 2** Problems caused by traditional caving mining

but also increasingly serious "three under" coal problem (that is, protective coal seam under water bodies, buildings, and railway), which seriously wastes coal resources and shortens mine service life. Western China is a fragile ecological environment area, which cannot bear the environmental damage caused by large-scale caving mining (Qi et al. 2016; Li et al. 2020a; Guo et al. 2020; Kang et al. 2019).

Therefore, faced with the environmental, safety, and social problems caused by the caving mining method, it has become an inevitable trend to transform traditional coal mining methods and develop green mining technologies. As an environment-friendly, safe, and reliable green mining technology, backfill mining cannot only realize the comprehensive utilization of solid wastes such as gangue and fly ash, but also effectively reduce surface subsidence. It has become a key content in the green mining technology system (Qian et al. 2018; Li et al. 2020b). Since 2012, the relevant departments of China have issued *the Environmental Protection Laws of PRC* and *the Guiding Opinions on Backfill Mining of Coal Mines* and other documents. Many provinces and cities have also issued documents to clearly and severely restrict waste dump and the discharge of solid waste. In addition, relevant departments have also increased support for backfill mining by means of resource tax reduction and capacity replacement, and have included backfill mining as an important part of the current evaluation index system for green mine construction in China (Tanushree et al. 2016; Chen and Zhao 2012). The importance of backfill mining is obvious. As one of the mainstream backfill technologies in China, paste backfill technology is mainly to make solid waste into a paste-like backfill material with a certain fluidity, and pump it to the backfill area through pipelines to achieve the purpose of surface subsidence reduction and solid waste treatment. This paper expounds the development status of paste backfill technology, analyzes the geological conditions of many coal mines using paste backfill technology, summarizes the applicable conditions of paste backfill technology, and finally points out the problems faced by the application of paste backfill technology, and makes a prospect.

## Research status of paste backfill technology

### Backfill material research

Paste backfill material (Chang et al. 2014; Chen et al. 2016) is a kind of paste-like material, which is mainly made by mixing coarse aggregate, fine aggregate, and cementitious material in a certain proportion with a certain amount of water. It has the characteristics of no critical flow velocity, no sedimentation, no bleeding, no segregation, and low compression rate. The components of paste backfill materials generally include coal gangue, fly ash, and cement. If the local coal mine gangue output is small, other solid wastes such as aeolian sand or construction waste are used to replace gangue as paste backfill materials. By using research methods such as orthogonal experiments and sensitivity analysis, Chinese scholars have studied the rheological behavior, pumping performance, and bearing capacity of paste backfill materials by using indexes such as bleeding rate, slump, setting time, and compressive strength (Wang et al. 2015; Tang et al. 2019; Cui and Sun 2010; Zheng et al. 2006; Liu 2013; Wang and Sun 2014; Zhao 2008; Shi et al. 2011; Li et al. 2016; Ren et al. 2014; Sun et al. 2012; Ding et al.2011; Li et al. 2020c). Figure 3 shows the common paste backfill materials and their research contents.

### Theory of strata control in backfill mining

The law of ground pressure behavior and the structural characteristics of overlying strata in the process of backfill mining are different from those of traditional caving mining method. Due to the existence of backfill materials, the ground pressure behavior is not obvious, and the deformation and subsidence of overlying strata are relatively gentle. In this regard, many scholars have studied the characteristics of overlying strata movement under the conditions of backfill mining (Zhang 2008; Miao and Zhang 2007; Zhang et al. 2010a; Liu et al. 2016; Zuo et al. 2019; Chen et al. 2012; Li et al. 2014; Li et al. 2020a, b, c, d), and a list of representative results is as shown in Fig. 4.

It can be seen from Fig. 4 that the equivalent mining height is the equivalent excavation height after the backfill body is fully compacted, which is related to the actual mining height, residual compaction degree of the backfill body, defective distance of roof-contact, and other factors. Continuous curved beam means that the roof behind the backfill panel will not collapse after the goaf is densely filled, but will bend and subside slowly, which is related to the dense backfill rate of the goaf and the mining height of the backfill panel. The elastic foundation beam and elastic foundation thin plate are based on treating the backfill body in the goaf as a foundation with certain elasticity, and the mechanical state of the roof sinking and moving on the elastic foundation is studied from two-dimensional and three-dimensional respectively. The temporal and spatial evolution of ground pressure is that in the process of advancing the backfill panel, the ground pressure behind it shows certain temporal and spatial characteristics.

Other scholars have also studied the structure and deformation characteristics of the overlying strata based on theories such as elastic foundation beams, and put forward the fruitful theories of strata control in backfill mining (Chang et al. 2011; Fan et al. 2018; Hassani et al. 2008; Ju et al.

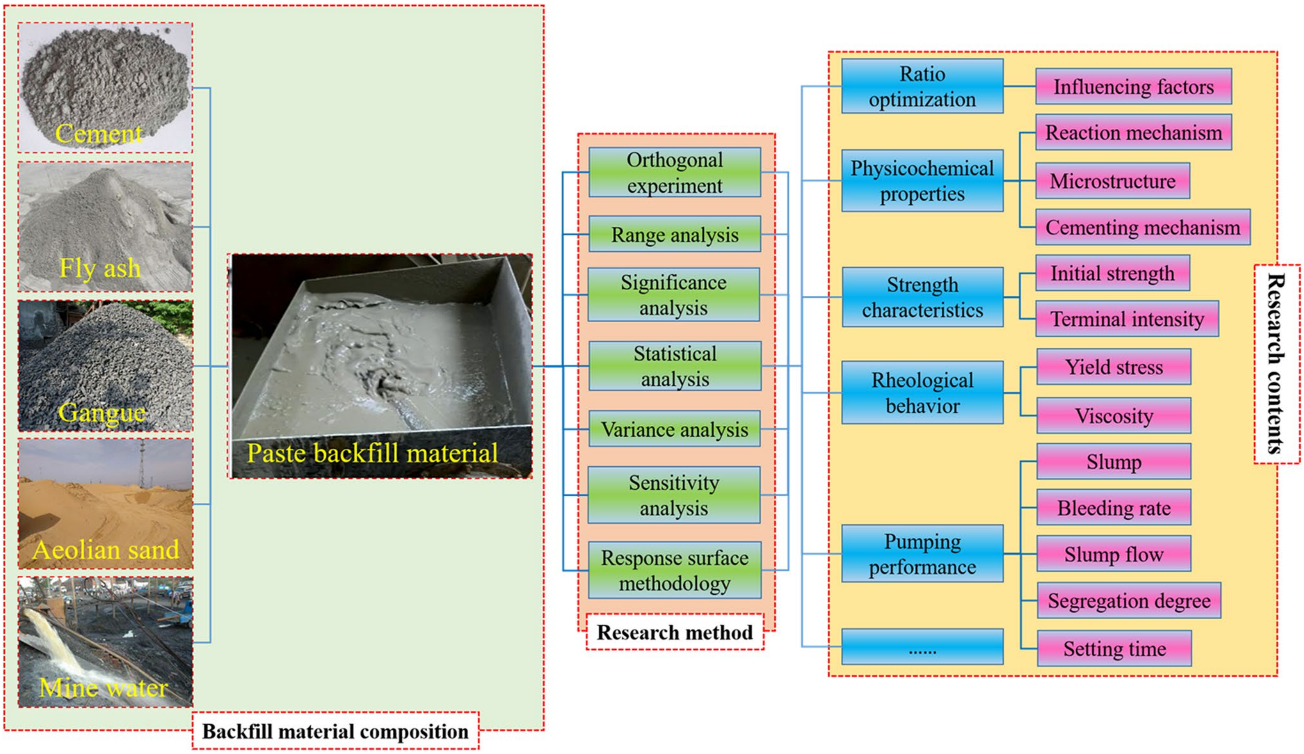



**Fig. 3** Research contents of paste backfill materials

2017; Zhang et al. 2010b; Wang et al. 2012; Yu et al. 2012; Chen et al. 2011; Huang et al. 2021).

## Paste backfill system and technological process

Paste backfill system mainly includes material preparation system, pumping system, workface backfill system, and monitoring and control system, the layout of backfill equipment is shown in Fig. 5. The material preparation system is generally located on the ground, its main function to mix and stir various backfill materials and water in a certain proportion in a mixer to make a paste-like backfill material with a certain fluidity. According to the different backfill materials, the composition of the material preparation system will be different. For example, the material preparation system with gangue as coarse aggregate also adds the crushing system of gangue, including the coarse crushing and fine crushing equipment of gangue; the material preparation system with aeolian sand as aggregate adds the impurity removal system, such as sieve shaker. The main equipment of paste backfill pumping system is backfill industrial pump and backfill pipeline. The backfill industrial pump is the heart of the whole paste backfill system, which provides power for backfill material transportation. At present, the maximum design flow rate of backfill industrial pumps produced in China can reach $400m^3$ per hour, and the maximum pressure at the outlet end of the pump can reach 25 MPa. The workface backfill system is different according to the workface layout in each coal mine, for example, some coal mines adopt strip backfill mining and some coal mines adopt comprehensive mechanized backfill mining. The monitoring and control system mainly includes the pipeline pressure and flow monitoring of the pipeline and the centralized control room, which is responsible for monitoring and controlling the safe and normal operation of the whole backfill system.

The basic technological process of paste backfill used in each coal mine is basically the same (Qu et al. 2004; Hu and Sun 2001). First, the materials used for coal mine backfill are stacked in the stockyard or storage bin. If the backfill material has a large particle size, the bulk backfill material will be crushed through two processes of coarse crushing and fine crushing. The small particle size material will pass through the weighing hopper, and then be transported by the conveyor or pipeline to the mixer for mixing and stirring with water. After the backfill material presents a paste state with a certain concentration and fluidity, it is poured into the slurry hopper, and the paste material is pumped into the pipeline leading to the underground by the backfill pump. Then, the paste backfill material is pumped to different backfill areas, such as goaf and bed separation, by adopting appropriate layout, such as complete mining and

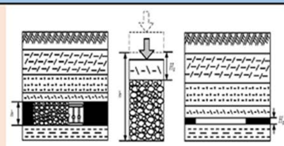
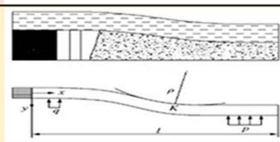
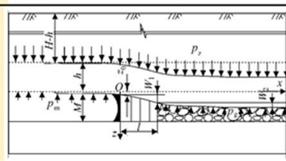
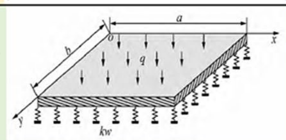
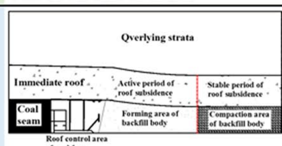
| Theoretical model of strata control | Schematic diagram of mechanical model | Mechanical formula | Interpretation of formula symbols |
|---|---|---|---|
| Equivalent mining height model |  | $H_z = h_w + (k_1 - k_2)(h - h_w)$ | $H_z$ is equivalent mining height; $h_w$ is defective distance of roof-contact; $h$ is mining height; $k_1$ is the loose coefficient of backfill body; $k_2$ is the compaction coefficient of backfill body. |
| Continuous curved beam model |  | $h_b = H_c - (H_c - U_1 - \frac{\alpha}{90 + 3R_{cw} + 250K_v})k_b$ | $h_b$ is the roof subsidence; $H_c$ is the mining height; $U_1$ is roof subsidence before backfill; $K_v$ is roof lithology influence coefficient; $R_{cw}$ is rock uniaxial compressive strength; $\alpha$ is different rock mass integrity factors |
| Elastic foundation beam model |  | $Z_g = \frac{p}{k} + z + w + e^{-\alpha x}[\frac{\alpha-\beta}{\alpha+\beta}(\frac{p}{k} + w)\sin \alpha x - (\frac{p}{k} + w)\cos \alpha x]$ | $Z_g$ is the roof subsidence; $k$ is foundation coefficient; $p$ is overburden load; $w$ is the subsidence before the roof contacts with the gangue; $z$ is the roof subsidence at x = 0 |
| Thin plate model of elastic foundation |  | $\omega = \sum_{m=1,3\ldots}^{\infty} \sum_{n=1,3\ldots}^{\infty} a_{mn} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b}$ | $\omega$ is the deflection of thin plate; $a_{mn}$ is the coefficient determining the deflection surface of thin plate; $a$ and $b$ are the width and length of thin plate, respectively |
| Ground pressure spatiotemporal evolution model |  | $\sigma = ae^{b\frac{\omega(Lt)}{h}} + c$ | $\sigma$ is the force of backfill body; $\omega$ is the roof subsidence deflection; $L$ and $t$ are the daily advancing distance and time of the backfill panel respectively; $h$ is the mining height. |

**Fig. 4** Strata movement model of backfill mining

partial backfill of gob, partial mining, and partial backfill of gob, as shown in Fig. 6.

## Application status of paste backfill technology

According to public information (Liu et al. 2020a, 2020b) and field investigation, the application of paste backfill technology in China's coal mines has been statistically analyzed, and the production capacity and quantity of coal mines using paste backfill technology in each province are plotted as shown in Fig. 7.

According to incomplete statistics, the current number of mines using paste backfill methods in China is about 38, and they are unevenly distributed. Most of them are concentrated in the northern areas north of the Huaihe-Qinling boundary, such as Shandong, Shanxi, and Hebei. Among them, the number of mines using paste backfill technology in Shandong Province is the largest, reaching 11. The number of backfill mines in Shaanxi, Inner Mongolia, and other provinces is on the rise, while the number of mines applying backfill mining technology in the ecologically fragile areas of western China is almost zero, indicating that the western region has a lot of room for development in solid waste treatment and the application of coal mine backfill technology. From the analysis of the annual production capacity of paste backfill mines, the number of large mines with a production capacity of more than 120 Mt/a using paste backfill method is the most, reaching 20, accounting for 52.63% of the total number of paste backfill mines. The number of backfill mines with a production capacity of less than 60 Mt/a is not many. Generally, small mines are resource exhausted mines with a long mining cycle, mainly using paste backfill to mine " three under" coal pillars.

## Analysis of typical paste backfill mine

According to the open data (Liu et al. 2020a), the parameters of paste backfill panel in typical mines are statistically analyzed, as shown in Table 1, the geological conditions and effect evaluation of typical paste backfill mines are statistically analyzed, as shown in Table 2.

The analysis in Table 1 shows that the longest paste backfill panel is 180 m, which is located in Taiping Mine. The shortest length is 15 m, which is room-pillar backfill mining, located in Jinxing Mine. The strike length of the backfill

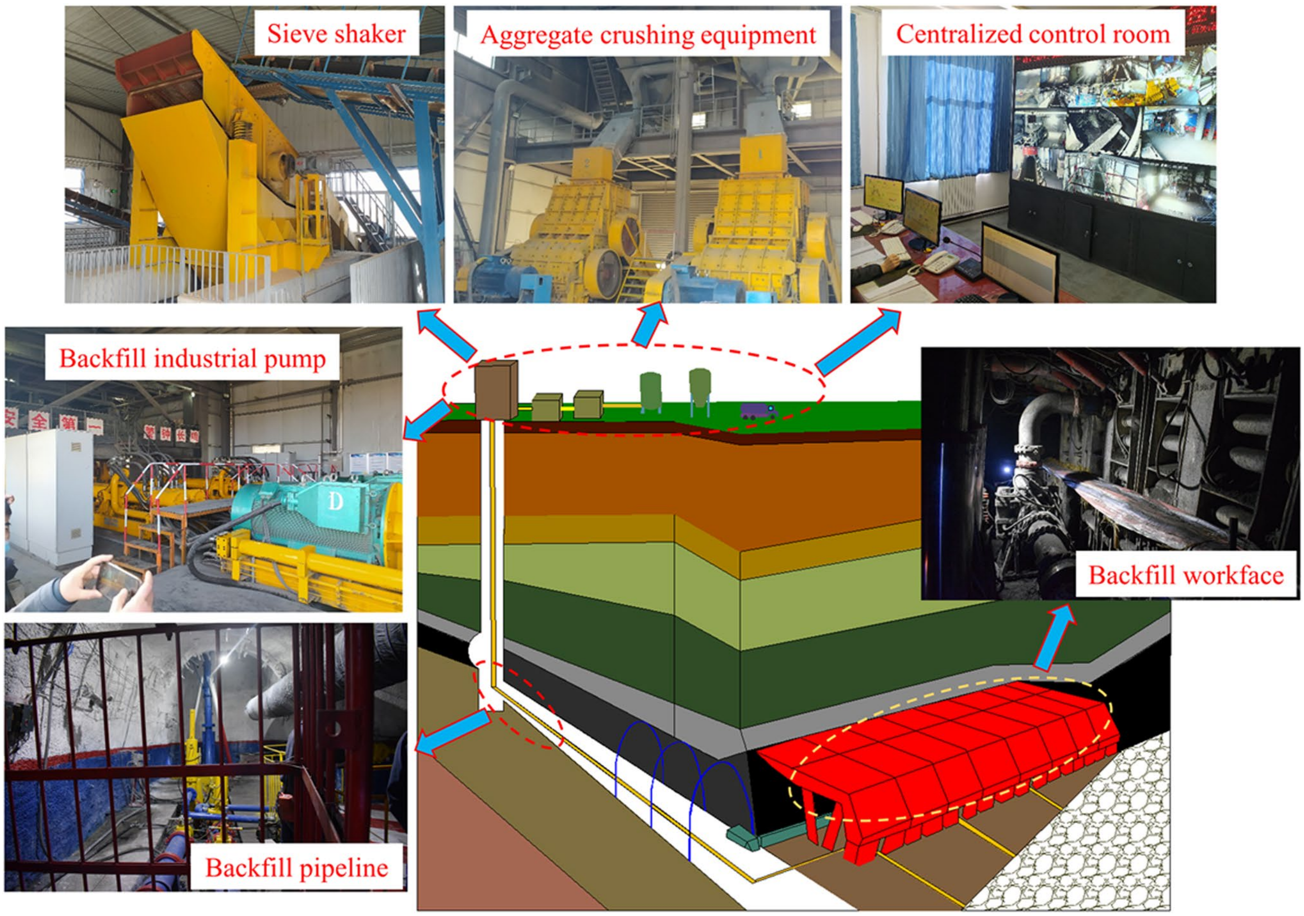



**Fig. 5** Partial equipment of backfill system

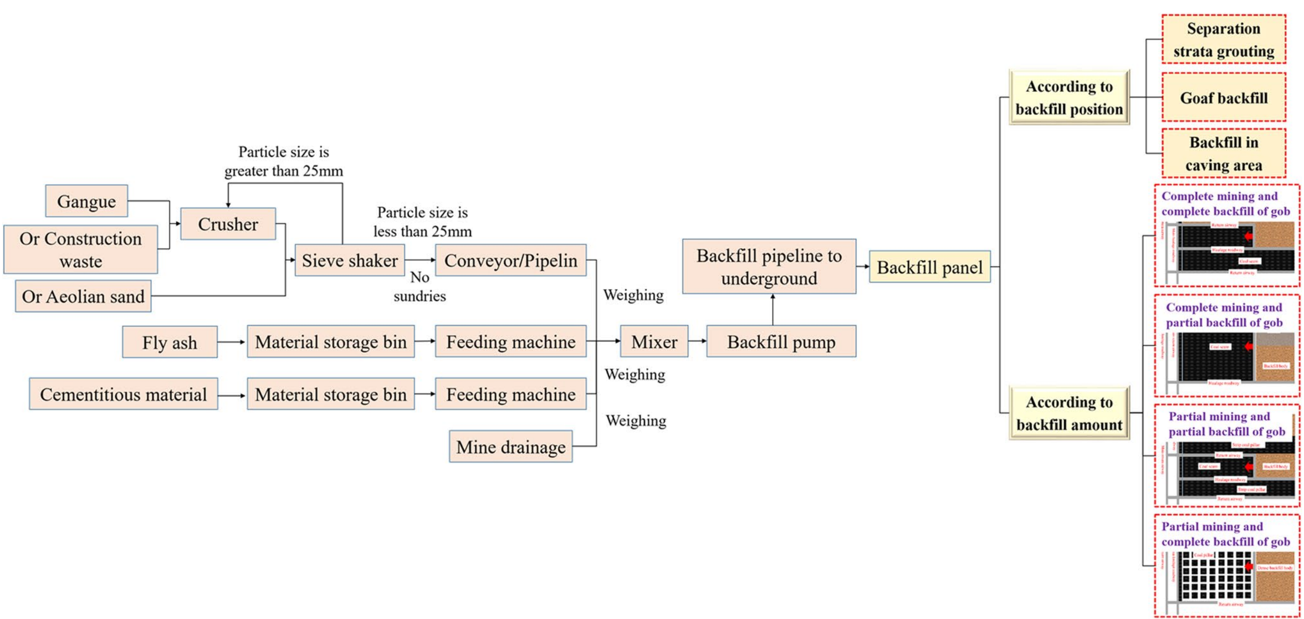



**Fig. 6** Schematic diagram of paste backfill technology process

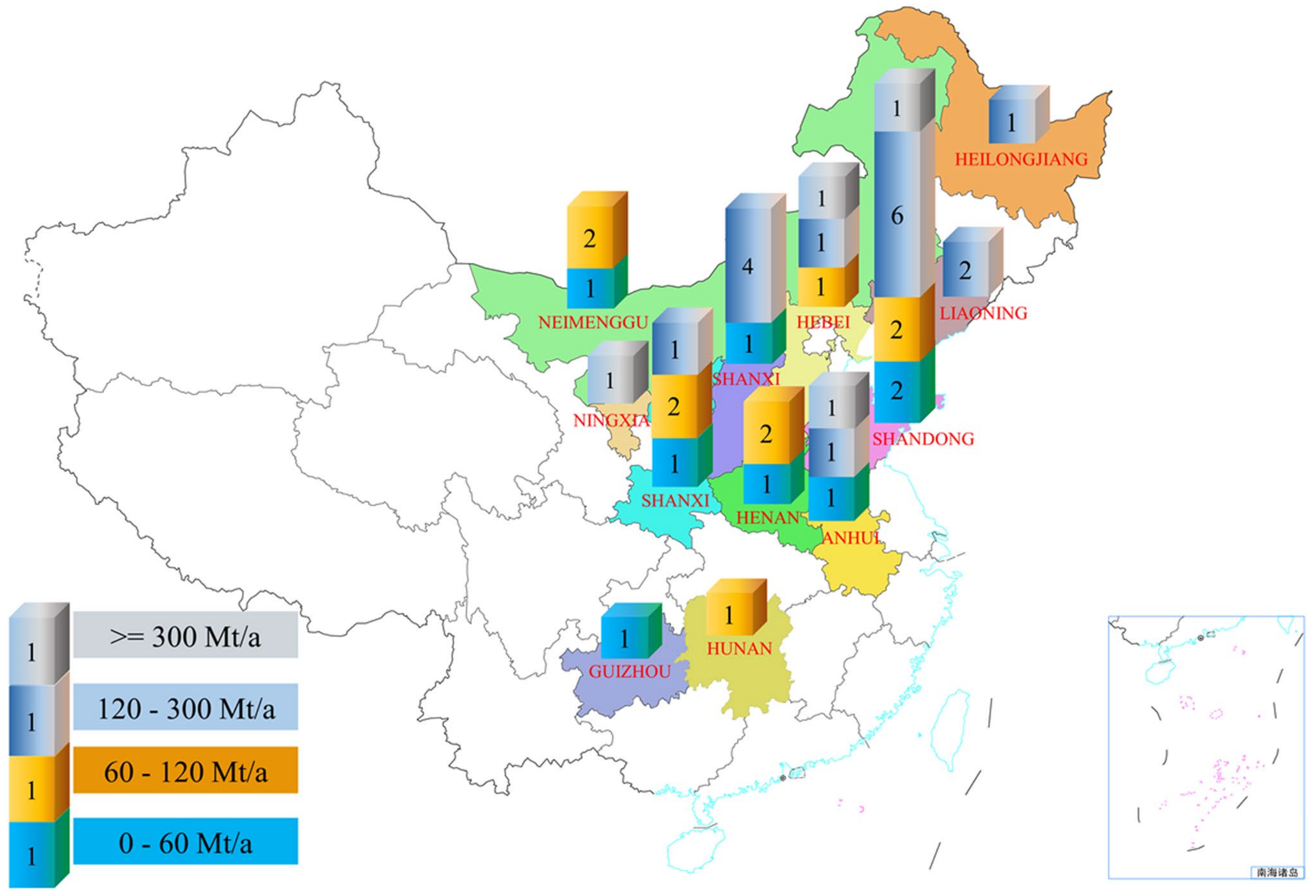



**Fig. 7** Distribution of paste backfill mines in China

panel is determined according to the actual conditions of the coal seam where it is located, but most of them exceed 250 m. The maximum buried depth of the coal seam where the paste backfill panel is located is more than 500 m, and the minimum is about 110 m, mostly 200–400 m. If the coal seam where the backfill face is located is thick, the slicing mining and backfill method is generally used. The height of backfill panel is generally less than 3 m, and the number of backfill panel with mining height between 2 and 3 m is the most. There are many backfill mines with coal seam dip angle below 20° and paste backfill is used in some coal seams with coal seam dip angle above 20° such as Suncun Mine, Tianyu Mine, and Daming Mine. When the coal seam dip angle is large, pseudo-inclined upward mining layout is mostly adopted in the backfill panel.

In Table 2, the immediate roof of the backfill panel in individual mines is a thin and unstable rock stratum, such as Taiping Mine and Zhangzhao Mine. However, the main roof of the paste backfill panel is mainly composed of thick and hard sandstone, which can slow down the subsidence speed of the roof in the process of paste backfilling and form a certain backfill space behind the panel. It can be seen that good roof conditions are favorable for paste backfill, but for paste backfill under broken roof, backfill mining is generally carried out by reducing panel parameters such as width and length, or by strip mining and room-pillar mining. The paste backfill panel is generally located in the coal pillar under the industrial square, village, and building with high protection level of surface buildings, or in the protective coal pillar with the aquifer in the roof and floor and threatened by confined water. The main reason is that the paste backfill material has high compactness and it is easy to arrange the backfill pipeline underground, which reduces the difficulty of backfill mining and the amount of surface subsidence. From the backfill effect of each mine, the surface subsidence above the paste backfill area is different according to the actual situation of each mine, The mine with the maximum surface subsidence is the Xiaotun Mine, that is, the maximum surface subsidence after two-layered mining is 700 mm, but the damage degree of surface buildings above the paste backfill area in each coal mine is within the scope of Grade I damage, indicating that paste backfill has a good application effect in coal mining.

**Table 1** Parameters of paste backfill panel in typical mine

| Name of coal mine | Inclination length / m | Strike length / m | The buried depth of coal seam / m | The thickness of coal seam / m | Coal seam dip angle | Remarks |
|---|---|---|---|---|---|---|
| Suncun Mine, Shandong | 70–100 | 340 | 380–570 | 2.1 | 17°–24° | |
| Daizhuang Mine, Shandong | 90 | 960 | 440 | 2.74 | 6° | |
| Caozhuang Mine, Shandong | 90 | - | 550 | 1.96 | 12°–29° | |
| Taiping Mine, Shandong | 160–180 | > 300 | 200 | 8.8 | < 5° | Slice mining, mining height is 2 m |
| Xiaotun Mine, Hebei | 120 | - | 410 | 5.5 | 6° | Slice mining, mining height is 2.7 m |
| Gonggeyingzi Mine, Inner Mongolia | 80 | 350 | 120–150 | 15 | 5°–14° | Slice mining, mining height is 2.7 m |
| Zhangzhao Mine, Shandong | > 100 | - | 202.5 | 2.8 | 4°–5° | Strip and jump mining method |
| Jinxing Mine, Henan | 15 | 15 | 180 | 6 | 4°–8° | Room-pillar backfill mining |
| Yangdong Mine, Hebei | 120 | 265 | 113.5 | 6.6 | 6°–10° | Slice mining |
| Tianyu Mine, Inner Mongolia | 135 | 150 | 140–200 | 3.57 | 15°–18°, locally up to 25° | |
| Zhucun Mine, Henan | 102 | 865 | 200–250 | 1.25 | 4° | |
| Daming Mine, Liaoning | 72 | 280–298 | 260–330 | 5.77 | 11°–20° | |

**Table 2** Geological conditions and effect evaluation of typical paste backfill mines

| Name of coal mine | Roof lithology | General situation of backfill panel | Evaluation of backfill effect |
|---|---|---|---|
| Suncun Mine, Shandong | The roof are soft and fragile mudstone, brittle siltstone, dense and hard sandstone | There are villages, schools, highways on the ground above the coal pillars | The amount of ground subsidence is very small, mostly within 10 mm, and the surface buildings are not damaged |
| Daizhuang Mine, Shandong | The roof is dominated by siltstone and medium sandstone | There are villages and schools on the ground, as well as railway lines and overpasses | Surface subsidence is small |
| Caozhuang Mine, Shandong | The roof is limestone, the floor is fine sandstone | The coal seam is threatened by the Ordovician limestone aquifer in the floor | There is no water inrush in the floor |
| Taiping Mine, Shandong | The immediate roof is siltstone. The main roof is fine sandstone | The surface above the backfill panel is Sihe River and its floodplain | The backfill effect is good |
| Xiaotun Mine, Hebei | The immediate roof is siltstone, and the main roof is fine sandstone | There are village buildings on the surface | The accumulated surface subsidence is 700 mm, the maximum tilt deformation is 3.0 mm/m, and the maximum horizontal deformation is 1.6 mm/m. The house damage is within the scope of Grade I damage |
| Gonggeyingzi Mine, Inner Mongolia | The roof is glutenite, intercalated with sandstone | There is aquifer above the backfill panel | The underground water inflow is obviously reduced, and the surface subsidence is relatively slight |
| Zhangzhao Mine, Shandong | The immediate roof is mudstone. The main roof is mainly siltstone, stable and medium-hard | There is Ordovician limestone aquifer in the floor | The surface maximum subsidence is 240 mm, the maximum horizontal deformation is 0.8 mm/m, and the maximum tilt deformation is 2.2 mm/m. The backfill effect is good |
| Jinxing Mine, Henan | The roof of coal seam is medium stable mudstone and sandy mudstone | The mining area is located in the coal pillar of the industrial square, and there are many buildings on the ground | The measured surface subsidence is less than 8 mm, and the surface buildings are not affected by mining |
| Yangdong Mine, Hebei | The immediate roof is siltstone, and the main roof is pebbly sandstone. The geological structure of the mining area is relatively simple | There are many villages and houses on the ground above the backfill panel | The surface subsidence is less than 140 mm, the maximum tilt deformation is 1.52 mm/m, and the maximum horizontal deformation is 1.72 mm/m. All subsidence indexes are within the allowable range of surface deformation value with Grade I damage |
| Tianyu Mine, Inner Mongolia | The roof is made of claystone and carbon mudstone | There are coal preparation plant, automobile repair plant and other buildings on the ground | The maximum subsidence of the surface is only 5 mm, which does not cause the damage of the buildings |
| Zhucun Mine, Henan | The immediate roof is limestone, and the main roof is siltstone and sandstone interbedding | There are many buildings on the ground and aquifers on the floor of backfill panel | The accumulated surface subsidence is 105 mm, the maximum tilt deformation is 1.2 mm/m, and the maximum horizontal deformation is 1.0 mm/m. The overall damage of buildings is still in the scope of Grade I damage |
| Daming Mine, Liaoning | The main roof of backfill panel is coarse sandstone, and the immediate roof is sandy mudstone, | There are railways, buildings and cultivated land on the surface | The maximum surface subsidence is 300–310 mm, and there is no obvious damage to the buildings |

## Applicable conditions of paste backfill mining

According to the analysis in Tables 1 and 2, the application conditions of paste backfill technology in China's coal mines are summarized as follows.

1. The materials needed for paste backfill, such as coarse and fine aggregates and cementitious materials, should be sufficient in quantity, widely sourced, and low in price. They should be made from nearby materials and made according to local conditions.
2. Because of the technical characteristics of paste backfill, such as high concentration, high strength, high roof connection rate, low compression rate, and good slurry pumping performance, the backfill technology can be widely used in the mining of thin and medium-thick coal seams under buildings, water bodies, railways, and above confined water.
3. In areas threatened by disasters such as water, gas, and rock bursts, the paste backfill method using pipeline pumping is relatively advantageous. Long-term backfill can be realized by arranging the pipeline once, reducing human–machine safety hazards.
4. Complex geological conditions and thin coal seam are more suitable for paste backfill. When the thickness of the coal seam is more than 3 m, slicing mining is generally adopted to make the height of the backfill panel less than 3 m.
5. Paste backfill is suitable for the geological conditions of coal seam with a certain dip angle, which can make full use of the fluidity of paste material to backfill the goaf. When the coal seam angle is large, the backfill panel is more suitable for the pseudo inclined upward mining layout.
6. The paste backfill system can be modified on a small scale on the basis of maintaining the original layout and equipment of the panel, the mining conditions that the roadway section is small, the mining space is narrow, and large machinery cannot enter are more favorable for the paste backfill method.
7. Paste backfill is suitable for the conditions of the large buried depth of coal seam and long distance of roadway due to the pipeline pumping method.

## Problems in the application of paste backfill technology

After years of development, paste backfill mining technology has been applied in many coal mines, and has obtained great ecological, economic, and social benefits. However, in the field investigation, it is found that paste backfill technology is still facing some problems in the development and application of coal mines in China, mainly including:

(1) Backfill material shortage and single material source

Coal mine paste backfill materials are mainly gangue, fly ash, and cement, most of the gangue comes from the coal waste piles accumulated on the ground for many years, and the amount of gangue produced in the process of coal mining and washing is very limited, which cannot meet the long-term and large-scale backfill application. Some coal mines produce less gangue, so aeolian sand is used to replace gangue. However, the long-distance transportation and high freight cost of aeolian sand limit the scale of paste backfill. Most backfill mines use gangue, fly ash, cement, and other common materials, but the amount of other solid wastes is small, which cannot be fully and effectively used, resulting in a single source and category of backfill materials, and a shortage of backfill materials.

(2) High investment in backfilling equipment and high cost of backfilling

This is the main problem faced by paste backfill technology in the development and application of China. After a coal mine decides to adopt paste backfill mining technology, it is necessary to build a backfill station and underground pipeline system. Equipment purchase and system construction need a lot of capital investment, and the cost of coal per ton will increase by more than RMB 50. This is undoubtedly a huge burden for small and medium-sized mines facing the depletion of resources and low coal price. In addition to the capital investment of backfill equipment, the mining and backfill processes often interfere with each other, seriously reducing the mining efficiency and production, further limiting the wide application of paste backfill technology.

(3) The problem of pipe blocking with backfill materials

In the laboratory, the backfill materials are prepared according to a certain proportion, the proportions of each component are accurate, and the paste properties are good. However, in the engineering field, due to a large amount of materials and many preparation equipment, the ratio error of backfill materials is often large, the fluidity of the backfill materials transported to the underground is reduced, and the problems such as large pipeline resistance and insufficient power exist in the process of long-distance material pumping, so the blocked pipe accident often occurs in the underground.

(4) The application of paste backfill is limited under complex geological conditions

At present, the geological conditions of the backfill panel using paste backfill technology are mostly good, the roof is complete and stable, and there is obvious backfill space behind the backfill panel. However, the application and research of paste backfill technology under complex geological conditions is less. For example, when the roof is weak and broken or falls along with the mining, since the goaf is filled with the collapsed roof, the size and orientation of the bed separation space above the collapsed roof cannot be accurately determined, which leads to the problem that the backfill pipeline cannot be smoothly arranged and the backfill is difficult.

## Prospect of paste backfill mining

Under the background of the new era, with the proposal of China's ecological civilization construction and ecological environment protection strategy, paste backfill technology has become an important part of the green mining technology system in China's mines, and undoubtedly has broad application prospects and development space in solving the problem of "three under" coal pillar. The author believes that while continuously perfecting the theoretical system, accumulating application experience and developing equipment technology, paste backfill mining can continue to develop from the following aspects in the future (Wu 2012):

(1) Research and development of new paste backfill materials

Paste backfill material is a very important part of paste backfill technology, which is related to the application effect of paste backfill technology. At present, paste backfill materials have shortcomings such as single source, high preparation cost, low initial strength, and easily blocked pipe, which affect the backfill effect and benefit. Therefore, it is necessary to enrich the components of paste backfill materials and develop a new type of backfill materials with a wide source of components, low preparation cost, and strong pumping performance. For example, in addition to common solid wastes such as coal gangue and fly ash, other coal-based solid wastes such as desulfurization gypsum and gasification slag can be added, which can not only supplement the shortage of gangue and fly ash, but also reduce the cement consumption and the preparation cost of paste backfill materials.

(2) Research on paste backfill methods suitable for complex geological conditions

At present, many backfill panel using paste backfill technology have good geological conditions. However, in complex geological conditions, such as large dip angle of the coal seam, roof easy to collapse, and other geological conditions, the number of mines using paste backfill technology is less. Therefore, with the development of backfill equipment technology and the accumulation of backfill application experience, research and development of paste backfill methods suitable for complex geological conditions have become one of the future development directions, which will help expand the scope of application of paste backfill technology.

(3) New mode of deep backfill mining

At present, the buried depth of coal seams using paste backfill is generally less than 800 m, while the number of panel with the depth of more than 800 m applying paste backfill technology is very small (Zhang et al. 2018). With the exhaustion of shallow buried coal resources in many coal mines, coal seam mining has a development trend toward deep underground. Coal mining in deep ground faces threats such as high ground stress and mining disturbance (Huang et al. 2020). Paste backfill mining can effectively alleviate the degree of strata behavior, reduce coal or rock dynamic disasters, and is suitable for long-distance material transportation, which is very beneficial for deep mining. Therefore, it is necessary to explore a new paste backfill mode suitable for deep underground environment in the future. For example, the construction of paste backfill station in the underground to shorten the transportation distance of paste backfill material. An grouting-backfilling roadway is arranged in the high-level rock stratum above the goaf, and paste grouting-backfilling is carried out in the bed separation of low-level rock stratum or the goaf. In this way, it is necessary to analyze the space–time relationship between roof movement and backfill support, so as to ensure that the bed separation space is filled with materials when it is the largest and the backfill body can support the roof in time.

(4) Develop intelligent paste backfill technology

At present, the intelligent development of China's coal mines is in full swing. Intelligent coal mining is the in-depth integration of modern science and technology with coal mining technology, through autonomous perception learning, the high-speed real-time interconnection of information, intelligent decision-making, and dynamic early warning, to form a safe, intelligent, and efficient operating system for precisely coordinated control of coal mining. Paste backfill technology can adopt intelligent mining equipment and means, intelligent technology can be developed in the backfill station intelligent batching system, precise positioning of pipeline blockage, optimized panel layout, precise backfill of bed separation space, and intelligent monitoring and control, so as to use high technology to guide backfill mining in coal mine.

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**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Ethical approval** Written informed consent for publication of this paper was obtained from the Anhui University of Science and Technology and all authors.

**Consent to publish** The author confirms that the work described has not been published before (except in the form of an abstract or as part of a published lecture, review, or thesis); that it is not under consideration for publication elsewhere; that its publication has been approved by all co-authors, if any; that its publication has been approved (tacitly or explicitly) by the responsible authorities at the institution where the work is carried out.

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