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Coal Mine Solid Waste Backfill Process in China: Current Status and Challenges

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Abstract: Coal mine solid waste backfill is a coal mining method employed to safeguard subterranean and surface geological formations, as well as water resources, against impairment. It stands as a pivotal technical approach for realizing ecologically sustainable mining endeavors, aiming to address China's predicament of 'three down' coal pressure, coal gangue emissions, and land resource scarcity. This manuscript delves into an in-depth exploration of the evolution and research status pertaining to solid backfill technology, encompassing backfill materials, rock mechanics, backfill processes, and their application across China's coal sector. The developmental challenges and technical intricacies linked to solid backfill technology within coal mines are meticulously scrutinized. Building upon these challenges and complexities, this study sets forth a progressive trajectory for solid backfill technology within the contemporary era. This trajectory envisions the synchronized advancement of novel solid backfill materials, intelligent surveillance and regulation methodologies, and machine learning technologies for backfill quality assessment. By doing so, the overarching aim of achieving superlative quality, heightened efficiency, and automation in solid backfill practices can be effectively realized.

Keywords: coal mine; solid backfill; progress; filling material; filling process; intelligent filling; applications

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1. Introduction

China is a prominent producer and consumer of coal. According to relevant statistics provided by China's National Bureau of Statistics, as depicted in Figure 1, coal production and consumption have historically served as the cornerstone of both primary energy production and the energy consumption structure. For example, in the year 2020, coal production amounted to 2.76 billion tons, constituting 67.6% of the overall primary energy production, while coal consumption stood at 2.83 billion tons, accounting for approximately 56.8% of the total energy consumption. [1] In the medium and long term, coal continues to play a central role in China's economic and societal energy landscape.

Due to the influence of deep coal seams [2], underground mining methods are commonly utilized in coal mining operations in China. Following the extraction of coal, a goaf is generated at its original location. The overlying strata can result in the collapse, fracturing, bending, and sinking of the upper strata of the goaf. This not only triggers strata-related incidents such as coal roof collapses and ground subsidence but also impairs the surface water system and underground stable aquifer within the mining area. Consequently, this leads to ecological damage and an elevated risk of coal mine water inrush accidents [3]. According to statistics compiled by Zhangpeisen [4] covering the period between 2008 and 2020 regarding domestic coal mine safety incidents, roof accidents accounted for 33% of the total incidents and were responsible for 31% of the total fatalities. Roof accidents constitute a pivotal category of accidents that necessitates preventive measures in coal mine safety operations. The issue of 'three-under' mining, which involves mining operations beneath buildings, railways, and bodies of water, poses a significant challenge in China [5]. Approximately 13.79 billion tons of coal have been subjected to compression due to 'three-under' mining activities, with building compression accounting for the majority at 63.5%, equivalent to 8.76 billion tons of the total coal compressed [5]. The coal compression underneath buildings in numerous mining regions has already reached a considerable 60% of the recoverable reserves. This situation has considerably impacted the coal recovery rate, presenting a serious impediment to production and development within these mining areas [6].

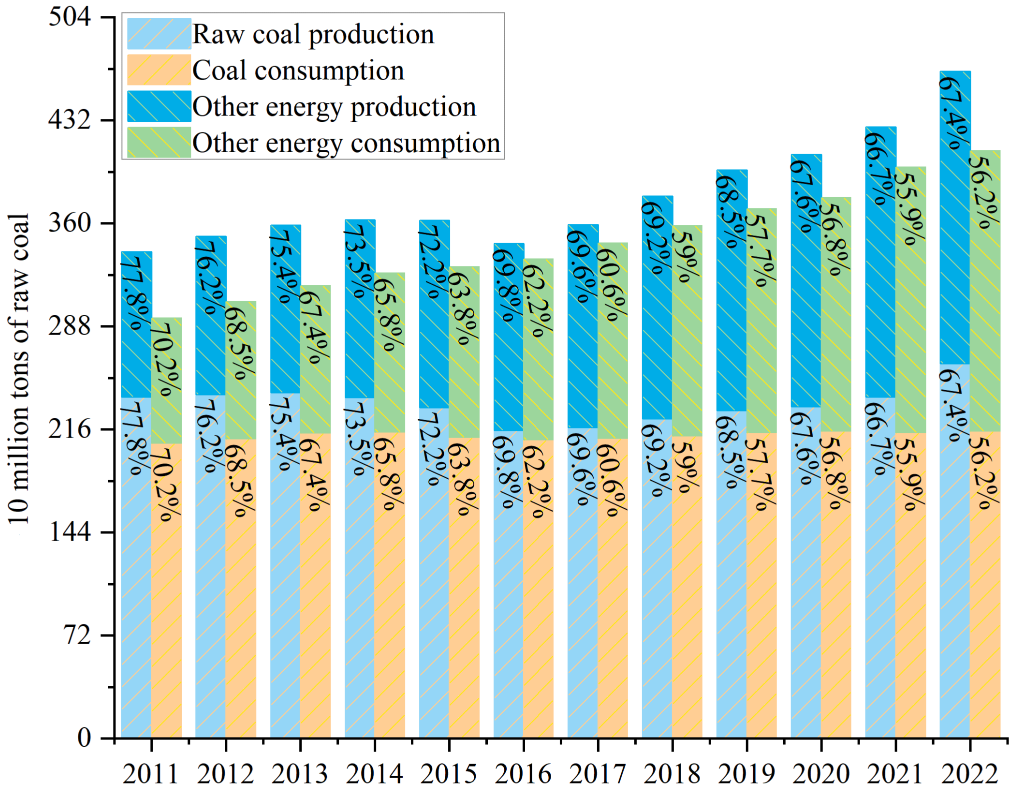

Figure 1. 2011–2020 China Energy Production and Consumption Statistics.

Coal gangue is a solid waste that is produced alongside coal mining activities. Prolonged outdoor storage of coal gangue not only results in land occupation but also leads to the emission or leaching of sulfides, which can contaminate the atmosphere, water bodies, and land. Additionally, coal gangue can pose risks such as fires and collapses during the rainy season, thereby causing disasters like river siltation. According to the "13th Five-Year Plan" for the coal industry's development, the annual production of coal gangue currently stands at 795 million tons. Within China's coal mines, there exist over 1600 accumulated gangue mountains, with a total quantity of approximately 4.5 billion tons and covering an area of about 15 km^2. Presently, the annual output of coal gangue ranges from 150 to 200 million tons, occupying an area of approximately 300 to 400 hm^2. Over the years, a total of 500 million tons of fly ash have been released from self-provided power plants within coal mine regions, with an annual increase of 50 to 70 million tons. The output of coal gangue makes up 10% to 30% of the raw coal or coal production. [7] According to data from the National Bureau of Statistics, China's raw coal output in 2020 reached 2.76 billion tons, and coal mining amounted to 3.9 billion tons [8]. It is estimated that the output of coal gangue is 400 million tons, with a comprehensive utilization rate of less than 30% [9].

In traditional coal mining, gangue was historically considered as an unusable byproduct and was often stockpiled around coal mines or directly released into the environment, resulting in significant environmental pollution and resource wastage [10]. The accumulation of substantial quantities of gangue not only consumes valuable land resources but also degrades the natural landscape and disrupts the delicate balance of the ecological environment. Additionally, gangue may contain hazardous substances, including heavy metals, that pose threats to both the environment and human health if left untreated, leading to soil and water contamination. Furthermore, the accumulation of gangue is frequently unstable and can trigger safety hazards such as collapses and landslides, jeopardizing the safety and assets of miners. The array of issues stemming from gangue storage significantly amplifies the production expenses and safety risks associated with coal mining operations. The degradation of the mine's ecological environment caused by coal mining, the destabilization of goaf resulting in mining accidents, and geological disasters like landslides triggered by unstable gangue mounds all pose substantial threats to the security and advancement of China's energy sector.

In the late 1960s, with increasing prominence of environmental issues and scarcity of mineral resources, the potential value of gangue resources began to be recognized by people. The concept of gangue resource utilization gradually emerged, involving the transformation of gangue from mines into useful resources like solid filling materials. This approach not only reduces waste generation and mitigates environmental pollution but also promotes resource recycling and enhances utilization efficiency. Concurrently, China initiated research and implementation of solid filling mining technology in coal mining regions.

Solid filling mining is a coal mining method that involves filling goafs with waste materials, such as gangue, fly ash, sand, gravel, and slag, either underground or on the ground. This method aims to control stratum movement, prevent surface subsidence, and safeguard underground and surface geological structures and water resource structures from damage [11]. Gangue filling mining stands as a significant technical solution for addressing China's "three-under" coal pressure, coal gangue discharge, and land resource challenges [12]. Encouraging the use of gangue filling mining techniques in coal mining can optimize the utilization of both coal seams and gangue resources, fostering harmony between economic benefits and environmental protection in mining regions [10].

The primary material utilized for backfilling is coal gangue, which is crushed and utilized as the principal solid filling material in the backfilling system. Other methods of backfilling primarily employ paste or slurry, such as utilizing industrial and municipal waste to create paste filling slurry for goaf backfilling. However, these methods necessitate large, fixed equipment, such as filling pumps and conveying pipelines. Ultra-high water material backfilling employs high-cost, rapidly solidifying materials for filling. In comparison to other methods, backfilling with coal gangue offers the advantage of low acquisition difficulty, stable material quality, and an easily manageable production process. In terms of equipment, solid filling equipment becomes imperative as the transported materials are solid. Scraper conveyors, filling brackets, and other transportation and filling equipment can be synchronized with the backfilling working face to enhance the portability and utilization rate of the equipment.

As mining technology has continued to advance, so too has the technology for solid backfill coal mining. One of the early pioneers of this method was the Bellair Mine in Australia, which adopted filling mining technology during the early 20th century. This approach was considered revolutionary as it utilized waste backfilling, including excavated coal slag and rocks, along with materials like cement, to fill goaf areas formed during the coal mining process. This not only improved ground support and safety but also prevented subsidence in the goaf. However, the filling technology shifted towards water-sand filling and slurry filling, leading to a decline in the use of the original waste rock dry filling technology after the 1940s.

In the 1990s, the Zhaizhen Coal Mine introduced solid gangue backfilling technology, achieving impressive results. Other domestic coal mines quickly adopted and implemented this technology, leading to rapid development. Initially, solid backfilling technology was limited to underground gangue treatment. It was not until 2008 that the Wugou Coal Mine and Yangzhuang Coal Mine achieved simultaneous coal mining and filling operations, expanding the use of solid backfilling technology to coal mining activities.

In 2012, the Tangshan Coal Mine established a comprehensive excavation and filling area, enabling integrated excavation and selection filling. After 2016, a new "mining–separating–backfilling+X" green mining system was introduced. This included engineering practices such as "mining–separating–backfilling+control", "mining–separating–backfilling+retention", and "mining–separating–backfilling+pumping". The development history of solid filling technology is illustrated in Figure 2. A comprehensive framework for solid gangue direct filling coal mining technology has been established. This framework effectively processes and fills waste coal gangue produced during underground coal mining operations, eliminating the need for above-ground gangue disposal. Based on existing technical frameworks, three types of gangue filling coal mining methods have been developed: fully mechanized filling coal mining, conventional filling coal mining, and roadway filling coal mining. These methods have evolved based on the geological conditions and mechanization levels of different coal mines [5].

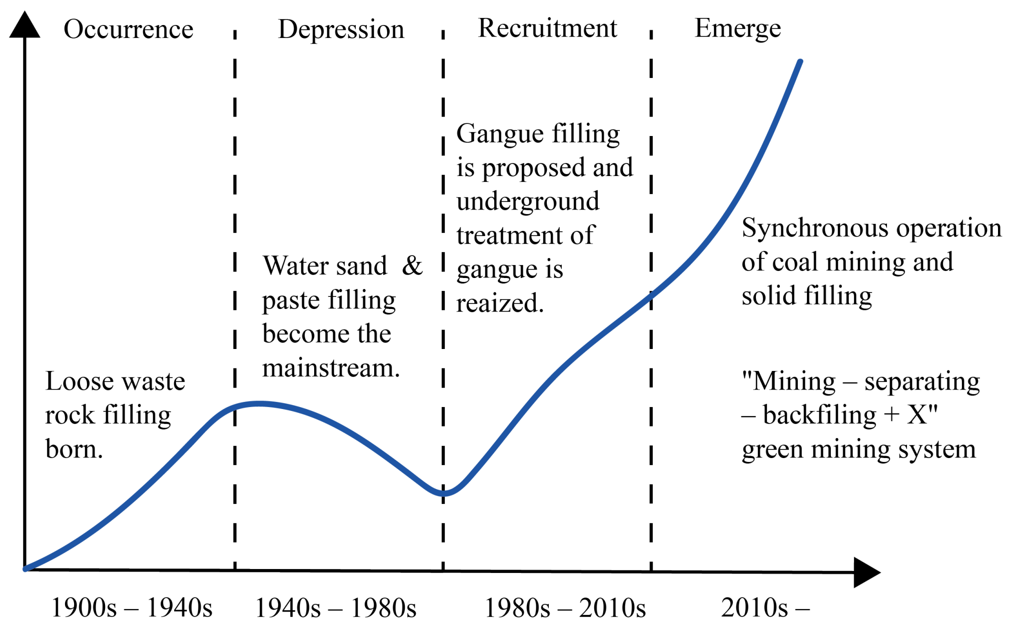

Figure 2. Development history of solid filling technology.

The comprehensive filling coal mining method is primarily used in highly mechanized mines with medium-thick coal seams. It involves immediately depositing gangue into the roadway and goaf after cutting the coal seam to minimize the goaf's impact on underground structures. The technical core of this method involves matching filling machinery and equipment with the comprehensive working face, such as self-compacting hydraulic supports and filling and mining conveyors [13]. The general mining filling coal mining method, commonly used in China, is applicable to general mining working faces. Research on this method is essential for promoting solid filling. The key equipment for this method is a high-speed dynamic dumping machine that enables dense filling of gangue in the goaf behind a single hydraulic prop working face [14].

Conversely, the roadway excavation filling coal mining method is suitable for mines with thicker coal seams, stable rock formations, and favorable geological conditions. This method allows for secondary excavation, filling the goaf with gangue immediately after one excavation is completed. The application of "gangue replacement column technology" enables the mining of remaining coal resources [15].

This article delves into recent advancements in solid gangue filling technology and its practical applications across various aspects. Firstly, the article outlines progress made in the preparation of solid gangue filling materials, including the selection of materials, mixing ratios, and filling effects. Secondly, it reviews progress in understanding and controlling the movement of overlying rock during the solid gangue filling process, with a focus on minimizing damage to the rock while controlling its movement. The article then introduces the solid gangue filling process and associated equipment, along with an evaluation of filling effects. Furthermore, it discusses challenges related to gangue filling, such as unsatisfactory outcomes and environmental concerns. Finally, the article suggests future development trends and proposes new ideas and methods for the application of solid gangue filling technology, while maintaining the original reference.

2. Preparation of Gangue Filling Material

Gangue is a solid grayish-black rock that contains lower coal content than coal and is commonly associated with coal formation. Conversely, fly ash, a by-product of coal combustion, accounts for producing 60–80% of the solid waste generated from coal-fired power plants. Coal mining inevitably generates a substantial amount of solid waste, including both gangue and fly ash. Typical solid filling materials are shown in Figure 3. Due to the limited usability of gangue, it is typically disposed of as waste. Presently, China has accumulated over 6 billion tons of gangue, surpassing all other types of waste generated within the country, and increasing at a rate of 5–8 tons annually. Therefore, utilizing gangue as a filling material can address safety concerns associated with coal mining spaces, while simultaneously mitigating ground pollution and optimizing the mine environment. As depicted in Figure 4, the gangue is screened and broken, resulting in gangue with varying particle sizes. The broken gangue is then used as the filling material and placed into the gangue bin. The retarder and fly ash from the binder bin and fly ash bin are released from the discharge port according to specified quantities. Subsequently, the binder and fly ash are conveyed to the mixing system through the transportation pipeline. The gangue, retarder, and fly ash are blended in a specific proportion and stirred for a designated period, ultimately forming the gangue filling material, which is then transported to the filling working face.

(a) Gangue (b) Coal Ash (c) Loess

Figure 3. Typical Filling Material: Gangue, Coal Ash, and Loess.

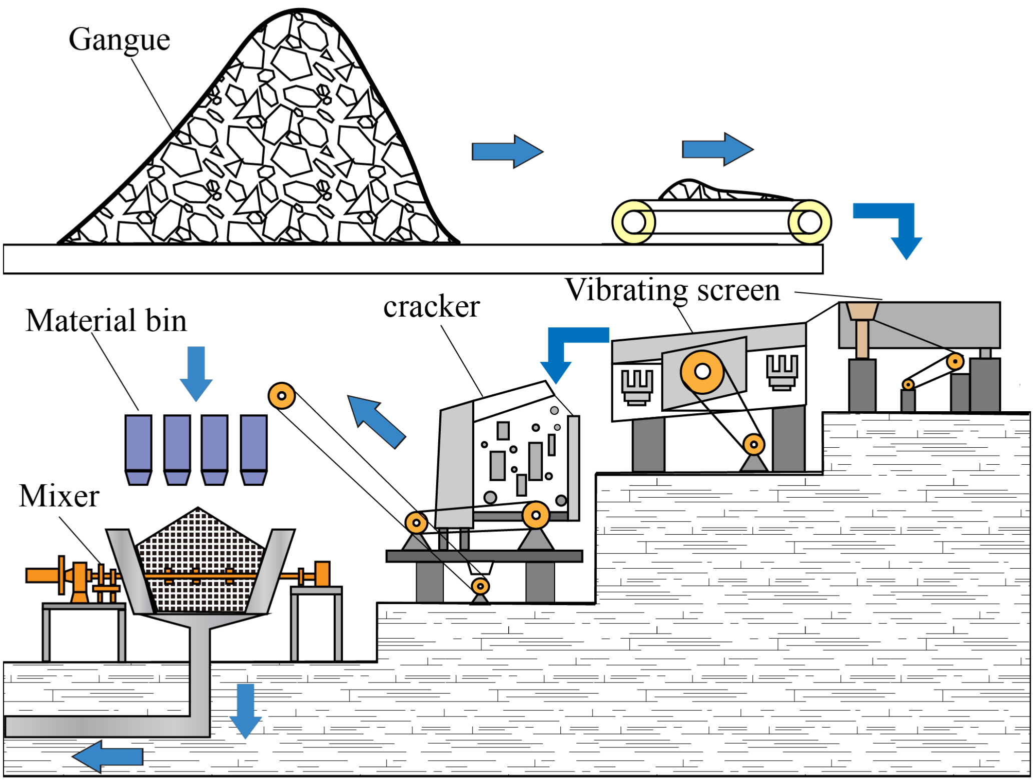

Figure 4. Preparation Process of Solid Filling Materials.

2.1. Composition of Gangue Filling Material

Table 1 illustrates the diverse applications of solid filling materials, such as gangue in coal mines, across various geological conditions in China throughout the 20th century. This table showcases the extensive range of uses for these materials in thin, medium, and thick coal seams. The incorporation of calcium oxide (CaO) elements in the majority of these filling materials enables them to transform into a gel-like calcium carbonate when combined with water. This compound undergoes a continuous hardening process during filling, ultimately leading to the formation of a stable filling body [16].

There is a wide variety of solid filling materials available, including solid waste such as gangue and open-pit slag. In some mining areas, local materials such as plateau loess and aeolian sand are also utilized. Fly ash, open-pit slag, and other solid wastes are often mixed with coal gangue and used as filling materials. This is supported by extensive research in the relevant literature and application in mining areas, particularly in Shanxi and Inner Mongolia. The selection and design of solid filling mining materials are crucial in developing process standards for filling mining working faces. They also provide a foundation for assessing filling quality, analyzing deformation characteristics of filling bodies and surrounding rocks, and predicting the deformation of overlying strata [17,18].

The primary objective of backfilling was initially to address the waste generated during the mining process. In the early 20th century, dry waste rock filling was utilized in Australian mines, such as the Mount Lyell Mine and North Lyell Mine in Tasmania, as well as in China in the 1950s, where mining waste was directly repurposed as filling material. However, these filling methods were found to be inadequate in providing sufficient support for the goaf, leading to increased mining workload and decreased production efficiency. Consequently, waste rock backfilling was swiftly phased out.

In the 1980s and 1990s, new mining filling technologies were developed as the previous methods no longer met the operational requirements or effectively reduced mining costs and environmental impact. These innovative techniques encompass high-density filling technology, paste filling technology, and block stone mortar cemented filling technology, which have been implemented in various underground mines worldwide. Notable examples include Australia's Cannington Mine, Canada's Kidd Creek Mine and Giant Gold Mine, Germany's Gronde Mine, as well as mines in South Africa, the USA, and Russia. Emerging filling processes and technologies have also been adopted in domestic mines, such as the Fankou Lead-Zinc Mine, Zhangmatun Mine in Jinan, and Xiangxi Gold Mine [19].

The preparation of paste materials involves the combination of cementing materials and aggregates, typically silicate cement and coal gangue. The high cost of paste filling is primarily attributed to the requirement for a significant amount of silicate cement and the utilization of specialized conveying equipment. In fact, filling costs usually account for approximately 20% of the total mining expenses, thus constraining the widespread implementation of filling mining technology [20]. However, in the late 20th century, the emergence of solid gangue filling technology offered a cost-effective alternative. This filling material primarily comprises gangue waste generated during coal mining, which is crushed and supplemented with fly ash, loess, and other materials. Following predetermined mixing ratios, the resulting mixture undergoes a hydration reaction, resulting in the formation of a cementitious material known as calcium carbonate. This material possesses favorable mechanical properties and provides advantages in supporting the goaf roof. Currently, solid gangue filling material has become the dominant choice for mining fillings. Ongoing research on solid filling materials predominantly centers on optimizing gangue and fly ash proportions, as well as enhancing adhesives and binding agents [20].

Table 1. Typical examples of filling mining in Chinese coal mines in the 20th century.

No.	Mine	Coal Seam	Application Time	Filling Material
1	Xinwen Mining Bureau	Gently inclined thick and medium thick coal seam	1956–1973	River sand
2	Hegang Xinyi Mine	Gently inclined thick seam	1952–1970	River sand
3	Fuxin Gaode Mine	thick seam	1956–1983	River sand
4	Fushun Shengli Mine	Inclined super-thick coal seam	1964–1972	Waste oil shale
5	Jiaozuo Yanmazhuang Mine	Gently inclined thick seam	1968–1970	Gangue
6	Fuxin Wulong Mine	Extra-thick seam	1972–1983	River sand
7	Jingxing No.4 Mine	Gently inclined thick seam	1969–1972	River sand and gangue
8	Nanjing Qinglongshan Mine	Inclined thin seam	1970	gangue
9	Huainan Kongji Mine	Gently inclined medium-thickness coal seam	1970–1979	Crushed stone
10	Jiaohe mine	Gently inclined thick seam	1971–1977	Gangue
11	Liaoyuan Taixin Mine	Gently inclined medium-thickness coal seam	1972–1973	Mountain sand
12	Guangzhou No.2 Mine	Steep medium-thick coal seam	1986–1989	Gangue

Data from <Review and development status of backfill coal mining technology in China> [21].

2.2. Research Progress of Filling Materials

Filling material plays a pivotal role in solid filling mining technology, as it presents significant potential to enhance mining efficiency, decrease mining expenses, and foster sustainable development in the mining sector. As a result, in recent years, extensive research has been carried out on solid filling materials, with a primary focus on scrutinizing their mechanical characteristics, particle size distribution, and proportions, as well as the techniques employed in synthesizing these materials from waste or novel sources. The results stemming from these research endeavors collectively have propelled the advancement of solid filling technology in recent times.

2.2.1. Mechanical Properties of Filling Materials

In recent years, extensive research has been conducted on the mechanical properties of backfill materials, shedding light on their pivotal role in determining the stability and overall performance of the filling structure. Various studies have demonstrated that factors such as differing ratios, strengths, deformations, and permeabilities of solid backfill materials can significantly affect surface settlement.

The influence of the solid backfill material's ratio and strength on surface settlement has been extensively studied, revealing their significant impact [22]. Conversely, the effects of deformation and permeability on surface settlement are relatively negligible. Furthermore, researchers have explored the time-dependent behavior of backfill materials in response to varying pressure conditions. It has been demonstrated that the backfill material enters a stable phase after a certain period, with deformation gradually converging towards a constant value [17].

In-depth analyses of the mechanical properties of individual solid backfill states have also been carried out. When the ratio of gangue to fly ash is 10:3, it has been observed that the compaction rate of the backfill material is minimized [23]. Furthermore, with regards to the mechanical behavior of mixed backfill materials, it has been discovered that the proportions of each component in the mixed material have an impact on strain and the modulus of deformation. For instance, as the mass of certain components decreases, strain increases while the modulus of deformation gradually decreases [24].

The microscopic properties of backfill materials, including particle size, friction coefficient, and porosity, also play a crucial role in determining the effectiveness of backfilling. Research studies have indicated that particle size has a significant impact on the rheological properties of the slurry within certain ranges, while the friction coefficient and porosity between particles have an influence on the overall macroscopic strain behavior of the backfill material [25,26].

Moreover, the mechanical properties of backfill materials are also influenced by environmental conditions. The strength and long-term deformation behavior of backfill materials are affected under acidic conditions. Experimental studies have demonstrated that the application of stress during the curing process can effectively enhance the strength of cementitious backfill materials [27].

In conclusion, the mechanical properties of backfill materials are influenced by various factors, thus requiring a thorough assessment of ratios, strengths, deformations, permeabilities, particle properties, and environmental conditions. These studies offer invaluable insights for enhancing the efficiency and stability of backfill materials in solid backfill mining projects.

2.2.2. The Influence of Composition on the Characteristics of Filling Materials

The performance of solid filling materials is significantly influenced by the particle size and particle ratio of waste rock in combination with other materials. In recent times, extensive investigations have been carried out to examine the impact of composition on the attributes of filling materials, resulting in a plethora of studies that have provided valuable insights. These research efforts have uncovered that the composition of backfill materials plays a fundamental role in shaping their mechanical properties and overall performance.

To commence, an investigation into the impact of particle size and confining pressure on the mechanical performance of coal gangue solid waste (GSW) reveals that the maximum bearing stress is more sensitive to confining pressure conditions rather than the distribution of particle sizes [28]. In parallel, another study focused on gangue backfill material underscores the influence of an appropriate particle size distribution on compression deformation. Smaller-sized gangue backfill materials can establish a stable framework structure, thereby enhancing their deformation capacity and reducing compression deformation [29].

Moreover, the proportion of components also exerts an influence on the characteristics of backfill materials. Research on coal gangue and fly ash backfill (CGFB) indicates that an increase in solid concentration leads to a reduction in pressure drop, and variations in the coal gangue to cement ratio in CGFB also impact pressure drop [30]. Similarly, studies demonstrate that for materials like granular coal gangue, alterations in solid content and particle distribution significantly impact porosity, permeability, and hydraulic characteristics [31].

Furthermore, the lithology of the backfill material has been a subject of investigation. Different lithologies of crushed stone backfill exhibit distinct compaction behaviors. Selecting appropriate lithologies for crushed stone and effectively controlling their particle size distribution and mixing ratios can improve the stability and stiffness of the backfill material [32].

In conclusion, these literature studies collectively reveal the impact of backfill material composition on its mechanical properties, deformation capacity, and hydraulic characteristics. These findings offer essential scientific principles for optimizing the design and utilization of backfill materials.

2.2.3. Preparation of New Filling Material

Recent research has investigated the utilization of waste resources as filling material, especially in cases where coal mine waste rock is scarce. For example, waste construction materials from urban areas can be crushed and mixed with waste rock to create filling material, as discussed in a study by the reference [33]. In recent years, scholars have explored the feasibility and advantages of this approach, as detailed in the work of the reference [34]. The study evaluated the physicochemical characteristics of various waste types, including tailings, construction debris, and fly ash, to assess their suitability for use as filling material in different mining conditions.

Another approach, proposed by the reference [35], involved the use of clinker-free steel slag binder (SSB) for mine filling. The results demonstrated that SSB exhibited superior mechanical properties and durability compared to cement, highlighting its potential for enhancing steel slag resource utilization and promoting environmentally friendly filling practices. Some mines have successfully combined waste rock, aeolian sand, and open-pit slag waste to create filling material with favorable outcomes, as reported in a study by the reference [36].

Additionally, the reference [29] investigated the feasibility of using a fly ash-slag based cementitious material as a mine filling binder to achieve goals of cost-effectiveness, environmental sustainability, and resource utilization. The cementitious material comprised municipal solid waste incineration fly ash, steel slag, blast furnace slag, and desulfurization gypsum, fully replacing traditional cement. The findings revealed that this material exhibited favorable mechanical properties, environmental stability, and the ability to effectively solidify tailings while mitigating the leaching risk of heavy metals and dioxins.

Various techniques can be employed in the preparation of filling materials, including cement solidification, chemical solidification, and physical solidification. Among these, cement solidification is the most widely used and well-established method. It utilizes cement as a binding agent to create a filling material with specific strength and stability. However, the use of Portland cement is associated with limitations in terms of both durability and sustainability. In light of these challenges, researchers have initiated investigations into the incorporation of novel materials into backfill compositions. This research aims to identify viable strategies for enhancing material performance and application through innovative approaches.

One such strategy involves the exploration of alternative binders or additives to enhance the performance of cementitious waste rock backfill (CWRB) or to reduce production costs [37]. This approach involves adjusting the composition of materials to improve strength, stability, and cost-effectiveness.

Another area of investigation involves the incorporation of industrial graphite oxide-fly ash (IGO-FA) composite materials as nano-modifiers to enhance the performance of cemented waste rock backfill (CWRB). This study demonstrates that the utilization of IGO-FA composite materials has the potential to improve mechanical properties, reduce permeability, and facilitate both high performance and environmental advantages, all while minimizing cement consumption in CWRB [38].

Additionally, the introduction of enhancers such as polypropylene fibers (PPF) has emerged as another approach to enhance the performance of backfill materials. PPF exhibits exceptional resistance to corrosion, tensile strength, and toughness, thereby contributing to enhanced crack resistance and ductility of the backfill materials. Research indicates that the incorporation of PPF can substantially enhance the long-term mechanical strength of modified magnesia slag-coal-based solid waste backfill materials (MPFB) [39].

The utilization of conventional solid filling materials composed of coal gangue and cement in mining applications can yield significant environmental repercussions stemming from pollution during the stages of production, preparation, and transportation. In response to this challenge, scholars have put forth alternative strategies for fabricating filling materials. One recent approach, as elaborated upon in the study by Guo et al. [40], entails the utilization of microbial-induced carbonate precipitation (MICP) technology for the creation of bio-mineralized gangue filling materials. Such materials are cultivated using Bacillus subtilis with heightened resistance, obviating the need for cement and thereby reducing the ecological impact. Additionally, the process of bio-mineralization enhances the micro-crystalline structure of the material, consequently contributing to its enhanced performance.

Another method for producing efficacious fillers within the mining domain is by harnessing nano-calcium carbonate (NCC) and natural volcanic ash, such as zeolite and pumice, as binders, which are blended alongside Portland cement (PC), as proposed by Hefni et al. [41]. The investigation revealed that the incorporation of NCC leads to improvements in early strength and uniaxial compressive strength (UCS) of the filler, while the introduction of natural volcanic ash bolsters long-term strength and durability.

Foam mine filling (FMF), a novel filler utilized in mining applications, is produced by blending preformed foam with a mixture of copper-nickel tailings and cement using a foaming agent. The resultant material possesses a lightweight and cellular structure. In a study by Hefni et al. [42], a method for preparing FMF is proposed and the effects of various factors on its performance are examined. Furthermore, the study compares FMF with traditional cemented fillers and assesses its benefits in underground mine applications.

Furthermore, a novel solid filling cementitious material comprised of fly ash, lime, cement, and water in specific proportions is presented by GSTC7 [43]. The authors analyze the fluidity, compressive strength, and permeability of the cementitious material under varying proportions and compare it with conventional cement slurry. The study concludes that the cementitious material exhibits high fluidity and compressive strength, low permeability and cost, and can effectively enhance filling efficiency and safety, as well as facilitate resource utilization and environmental protection.

In summary, these alternative approaches hold the potential to mitigate the environmental impact of mining activities, while simultaneously enhancing the strength and durability of filling materials employed in the industry.

3. Study on the Movement Law and Control of Overlying Strata in Gangue Filling Mining

3.1. Mine Pressure Appearance-Basic Characteristics of Mine Pressure

Mining sites play a critical role in extracting valuable mineral resources. However, the mining process can lead to the deformation and fracture of ore and rock, generating mining pressure that can greatly impact the stability and safety of the site.

The manifestation of mining pressure refers to the appearance of pressure induced by mining activities during the mining process. This pressure can arise from changes in geological and mechanical conditions affecting the mining site. The manifestations of mining pressure include surface deformation, rock fracture, and coal seam outbursts, all of which can have a significant impact on the mining operation.

Surface deformation is a manifestation of mining pressure that occurs on the surface and can result from various factors. It includes surface subsidence, surface uplift, and ground fissures. Surface subsidence is the most common form of surface deformation, resulting from the collapse and settling of the goaf and rock layers. Surface uplift generally occurs due to pressure changes in the surrounding rock of the goaf, and ground fissures are formed by the fracturing of rock layers.

Rock fracture is a manifestation of the stress exerted by mining activities, resulting in the development of cracks and fractures within rock layers. This phenomenon occurs when the stress within the rock layers reaches their strength limit. The consequences of rock fracture include the loss of coal or ore, an increase in mining difficulty, and a substantial impact on the stability and safety of the mining site.

One particularly hazardous outcome of mining pressure is coal seam outburst, where a coal seam suddenly protrudes to the surface due to the pressure generated during mining activities. This dangerous phenomenon can lead to coal mine accidents, causing both casualties and property damage [44].

Mining pressure encompasses the stress and deformation brought about by ore mining activities within mines. It comprises three types of stress: geological stress, initial stress, and mining-induced stress.

Geological stress pertains to the inherent stress state of the earth and encompasses both vertical and horizontal stress components. It is the most fundamental source of stress in mining and exerts a significant influence on the stability and safety of mining operations.

Initial stress pertains to the stress condition of the ore prior to the commencement of mining activities. This encompasses both the geological stress and the initial stress caused by the deformation of rock layers. Initial stress significantly influences the stability and safety of mining operations.

Mining-induced stress, on the other hand, emerges as a consequence of ore mining activities. This category of stress encompasses several components, including roof stress, floor stress, and sidewall stress. Mining-induced stress stands as the most pivotal source of stress within the mining context and directly impacts the stability and safety of mining operations.

Upon the extraction of coal, the formation of goaf disrupts the original equilibrium state of the rock strata. The reconfiguration of stresses within the neighboring rock layers triggers movement and deformation within the rock mass, leading to phenomena such as roof collapse, floor heave, and the concentration of stress on support structures. This concentration of stress on support structures is known as mining-induced stress. Throughout the process of backfill mining, the supports and filling materials assume a critical role in providing support to the goaf region. Consequently, this alteration affects the stress distribution on the roof, thereby ameliorating the rock layer deformations induced by mining pressure.

Figure 5 elucidates the structural attributes of rock strata during the process of backfill mining. The goaf region situated behind the active mining face gains support from hydraulic supports embedded within the filling material. This strategic arrangement curtails the possibilities of roof collapse and subsidence. Adjacent to the hydraulic supports lies the filling material, which, upon attaining a specific degree of consolidation, adeptly mitigates stress concentration at the proximate roof level.

As the mining face progressively advances, the immediate roof undergoes a gradual subsidence, marked by its sustained integrity without any fracturing or collapse. This subsidence phase corresponds with the compaction of the filling material, thereby augmenting its mechanical efficacy and engendering heightened supportive force. Ultimately, a state of equilibrium materializes, harmonizing the interactions between the roof and the filling material. The roof, propped by the filling material, adopts a distinctive arch-like configuration. This curvature effectively diffuses stress transfer within the superjacent rock layers, orchestrating controlled movement of the rock mass and thwarting any surface subsidence.

In synthesis, the application of backfill mining alongside strategic reinforcement via filling materials and hydraulic supports engenders a harmonized interplay between the roof and the filling material, culminating in an arched configuration. This arrangement facilitates stress propagation across the overlying rock strata and efficaciously governs the movement of the rock mass, concurrently averting surface subsidence.

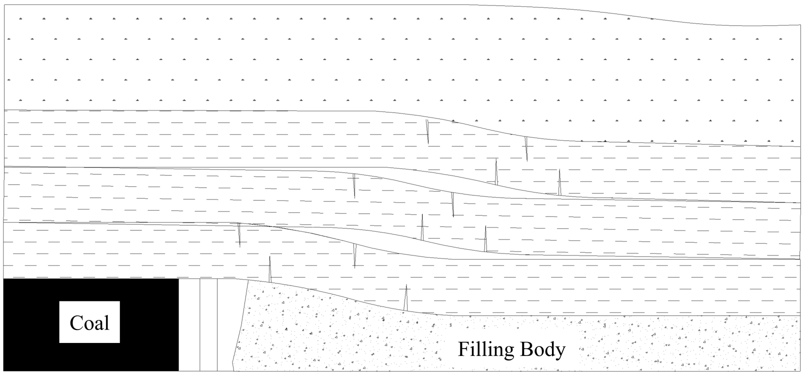

Figure 5. Structural Characteristics of Backfill Mining Rock Strata.

Undoubtedly, the considerations of both mining pressure and its manifestation stand as pivotal concerns within the realm of backfill mining. The intricate interplay of the mining procedures engenders alterations in the stress states of ore, subsequently instigating surface deformations, rock fissures, and even occurrences of coal seam outbursts. These phenomena collectively wield a substantial influence upon the overall stability and safety of the mining locale.

In the pursuit of ensuring a secure and steadfast mining environment, the consistent monitoring and adept control of mining pressure emerge as imperative requisites throughout the mining trajectory. By undertaking proactive surveillance and judiciously governing the trajectory of mining pressure, the groundwork is laid for devising efficacious strategies. Such strategies wield the potential to mitigate the frequency and ramifications associated with the manifestation of mining pressure across the mining expanse.

3.2. Deformation Characteristics of Rock Mass

During the process of backfill mining, the intricate interplay between the coal seam and the rock mass can give rise to deformation and damage within the rock mass. This deformation and resultant damage bear substantial ramifications on operational safety and the overall quality of the backfilling procedure. Consequently, a profound significance lies in delving into the deformation attributes exhibited by the rock mass in the context of gangue backfilling mining.

The deformation characteristics of the rock mass in the realm of gangue backfilling mining primarily encompass three distinct categories: elastic deformation, plastic deformation, and failure.

Elastic deformation manifests as a reversible phenomenon wherein the rock mass generates elastic strain when subjected to external stresses. Upon the removal of these stresses, the rock mass reverts to its initial configuration.

In contrast, plastic deformation constitutes an irreversible course of action, unfolding when the rock mass confronts stress surpassing its threshold strength. In such instances, the rock may undergo permanent alterations in its shape.

The ultimate phase of rock mass deformation culminates in failure, marked by the fracturing and cleaving of the rock.

The classification of rock mass deformation hinges on an array of influential factors, encompassing rock properties, geological conditions, and the prevailing stress state [45]. Grasping the intricate nuances of these characteristics assumes pivotal importance within the domain of effective gangue backfilling mining. This comprehension serves as a bedrock for prognosticating and mitigating the prospects of rock mass deformation and damage, thereby orchestrating an augmentation in operational safety and the caliber of the backfilling process.

Stress stands as arguably the foremost determinant shaping the deformation characteristics within gangue backfilling mining. The magnitude and orientation of stress exert a profound influence on the deformation conduct of the rock mass. Additionally, the rock's strength and stiffness interplay with its deformation tendencies.

Temperature alterations represent another pivotal variable that may impinge upon rock mass deformation. Variations in temperature can induce thermal expansion and contraction within the rock mass, further accentuating its deformation. Similarly, shifts in moisture content can induce swelling and contraction, thereby amplifying the potential for deformation.

Crucially, the geological parameters and rock attributes, including the mineral composition and structural configuration of the rock mass, emerge as supplementary influencers of deformation conduct. A comprehensive grasp of these variables assumes paramount importance for the efficacious governance and oversight of rock mass deformation within gangue backfilling mining undertakings.

The deformation of the rock mass constitutes a pivotal determinant underpinning the effectiveness of gangue backfilling mining endeavors. Through an exploration of the motion within the overlying rock strata, the occurrence of surface subsidence, and the stress-induced deformation of the backfilling material, researchers can discern the effectiveness of the backfilling technique, ensure the safety of workers, and curtail environmental ramifications. Consequently, in recent years, a multitude of scholars have engaged in rigorous research endeavors focused on these subjects.

The displacement and distortion of the superjacent rock strata hold a pivotal significance in ascertaining both the efficacy and safety of gangue backfilling mining. As a result, comprehending the mechanisms governing the movement and deformation of these overlying rock strata stands as an imperative consideration within the realm of solid backfilling mining.

Consequently, researchers have directed their efforts toward the investigation of the spatiotemporal configuration of the overlying rock strata and its consequential impact on migration throughout the process of strip pillar mining and backfilling. A noteworthy instance lies in the work of Chen et al. (2011) as presented in [46]. In this study, the authors undertook a comprehensive exploration of the spatiotemporal structure inherent to the overlying rock strata, delving into its intricate influence on the migratory phenomenon during the course of mining and backfilling operations. The outcomes of their investigation unveiled a discernible trend: as the working face progressively advances, the spatial structure of the overlying rock strata undergoes a metamorphosis, transitioning from a spatial arrangement akin to the letter "C" to an unequal height supported hinged rock beam structure.

Investigation by Reference [47] centered on the dynamic behavior of overlying rock strata within a backfilling coal mining working face. This inquiry was achieved through compaction characteristic tests conducted on backfilling materials. The authors aimed to establish a correlation between the elastic modulus of the backfilling material and the resultant vertical strain. Employing numerical simulation techniques, the study simulated the effects of diverse backfilling methods and materials on the movement of rock strata. This endeavor was further substantiated by the validation of simulation outcomes through comparison with field measurements.

Reference [48] delved into the intricate movement patterns of the surrounding rock during the process of recovering residual coal pillars. The study derived a spectrum of calculation formulas to expound the stress, displacement, and spatial extent of the plastic zone within the enveloping rock. Moreover, the research encompassed simulation of multifaceted phenomena, including the deformation of the surrounding rock, instability of coal pillars, and the impairment of abandoned roadways under distinct operational conditions. The authors distinguished between two underlying mechanisms of instability during the residual coal pillar recovery phase: overarching instability attributable to the subsidence of the overlying rock strata and localized instability occasioned by the enlargement of abandoned roadway apertures.

Meanwhile, Reference [49] undertook an exploration of the intricate interplay between backfilling mining support and the adjacent rock strata. An in-depth analysis of the movement traits of the superjacent rock strata was conducted. Additionally, the study scrutinized the operational resistance of hydraulic support mechanisms and employed periscope-based observations to ascertain roof delamination phenomena within the context of the backfilling working face. The authors ascertained that elevated operational resistance of the support apparatus can effectively govern roof subsidence, mitigate damage to overlying rock, and effectively regulate surface deformation.

Surface subsidence represents a prevalent challenge within the coal mining process, exerting far-reaching effects encompassing mining efficiency, safety, and the local environment. The pursuit of effective strategies to regulate and diminish subsidence has captivated the attention of numerous scholars in recent years. Reference [50] introduced a groundbreaking backfilling mining technique named pier column backfilling mining (PCBM). This innovative method integrates cement-solidified binder material in the form of pier columns within the goaf. These pier columns provide essential support to the overlying rock strata, thereby exercising control over surface subsidence. Empirical evidence derived from the Wangzhuang coal mine attests to the manifold merits of this approach, including both environmental and economic benefits, coupled with its capacity to effectively govern surface subsidence.

Moreover, Reference [51] presented an approach rooted in the equivalent mining height (EMH) theory for predicting and managing surface subsidence. Notably, the compression ratio of the backfill body (BBCR) emerges as the pivotal controlling parameter. The authors methodically devised a comprehensive engineering design procedure for solid backfilling mining, implementing this methodology within the Huayuan coal mine. Encouraging outcomes underscored that this method is adept at reining in surface subsidence, yielding an impressive 60% reduction as compared to traditional mining techniques under analogous operational circumstances.

Furthermore, Reference [52] advanced a predictive methodology geared towards surface subsidence in backfilling strip mining. The authors adroitly partitioned surface subsidence into two constituents: backfilling mining and strip mining. Corresponding prediction models were methodically established for each component. These models were subsequently harmonized via the conventional probability integral method, culminating in a comprehensive prediction model for surface subsidence. Rigorous verification was conducted through theoretical deduction and numerical simulation, in addition to a rigorous comparison with field monitoring data. The outcomes definitively validate the precision and practicality of this technique in accurately forecasting surface subsidence during backfilling strip mining.

Solid backfill mining heavily relies on the robustness and stability of the fill material, a pivotal aspect crucial for both mining efficiency and safety. Investigating the mechanical characteristics and control mechanisms governing the stability of fill material bears the potential to elevate its strength and stability. Notably, Reference [53] introduced an analytical approach grounded in damage mechanics and energy principles, aimed at deducing material ratios and fill strength. A damage-based constitutive model was formulated for the pre-peak stress stage of fill material, encompassing elasticity, plasticity, and damage phases. Analytical expressions for optimizing fill strength and ratio were established, grounded in the concept of equivalent peak deformation energy and the release of energy from excavated rock mass. This method's viability and effectiveness were subsequently substantiated via numerical simulations and real-world tests, thus furnishing a scientific bedrock for fill material design.

In a parallel vein, Reference [54] advanced a stratagem to govern stress–strain dynamics within rock masses by deploying fill materials of varying strengths. This tactic aimed to mitigate the mining-induced impact on rock mass stability. A numerical framework was developed, accounting for the interface between rock and fill and accounting for variations in fill strength. The influence of disparate fill strengths on the stress–strain characteristics of the rock mass was examined. Substantiation of this approach's effectiveness transpired through field experiments, attesting to its potential in ameliorating both rock mass and fill stability.

Moreover, Reference [55] undertook an exploration of the ramifications of mining depth and adjacent mining activities on side-exposed fill stability. This inquiry encompassed the analysis of failure mechanisms and cohesion diminution within the fill material. Identification of the primary failure mechanism and the interplay between rock creep effects and side-exposed fill stability ensued. Additionally, the repercussions of adjacent mining temporalities and sequences on fill failure were evaluated, offering valuable insights into this intricate aspect.

Addressing the aspect of fill ratio, Reference [56] pioneered a design approach rooted in fill material compression characteristics. The authors established a predictive model linking fill material compression ratios with mining parameters, predicated on the analysis of the deformation tendencies exhibited by fill material under diverse conditions. By integrating the principle of minimal total cost, an optimal fill ratio design methodology was conceived. The approach's efficacy and feasibility were verified through theoretical analysis, on-site trials, and monitoring endeavors within an active mining locale, culminating in commendable outcomes.

Lastly, Reference [57] crafted a dynamic model elucidating upper rock subsidence, predicated on the Knothe time function. This model facilitated an examination of roof subsidence dynamics across temporal progression during backfill mining. Additionally, a predictive model capturing dynamic surface subsidence was formulated, integrating variables like interlayer displacement angle, interlayer displacement ratio coefficient, and accounting for fill material attributes such as strength, thickness, and dip angle. The outcomes highlighted the feasibility of expressing the subsidence process in exponential terms as a function of time, thereby encapsulating the evolving nature of backfill mining roof subsidence.

Collectively, these references offer a comprehensive panorama of methodologies and insights crucial to augmenting the strength, stability, and efficiency of solid backfill mining processes.

4. Gangue Solid Filling Mining Technology

The waste rock filling process can be categorized into three distinct stages according to the procedural flow: the sorting and batching stage, the waste rock transportation stage, and the waste rock filling goaf stage. Within the filling stage, further classification is possible, differentiating between roadway filling and working face filling, contingent upon the specific objects of filling space.

4.1. Filling Material Sorting and Batching System

The segregation and arrangement of waste rock constitute pivotal facets of waste rock filling in mining operations. In the segregation phase, the raw coal and waste rock undergo classification to procure suitable waste rock for the filling process. In the subsequent configuration step, the waste rock necessitates amalgamation with auxiliary fillers, with careful regulation of the mixing proportions aimed at ensuring optimal filling quality and enhancing coal mining efficiency.

Presently, several subterranean separation methods for coal gangue are prominent, including selective crushing, shallow screening utilizing heavy medium separation, vibrating screen stratification, water-based selection, and X-ray identification [58]. Among these approaches, heavy-medium separation stands out as a prevalent technique, leveraging discrepancies in specific gravities between coal and waste rock to accomplish effective separation.

Solid materials employed for backfilling necessitate the incorporation of auxiliary substances, such as fly ash or loess, to amplify compaction effects. The judicious determination of the proportion between primary and auxiliary materials is pivotal to attaining an optimum backfilling outcome. Additionally, it is imperative to ascertain the suitable moisture content of the backfilling material, contingent on the compositional ratio of the constituents.

Illustratively, the cement filling mining technique entails the amalgamation of cement with waste rock or tailings to serve as fillers, bridging gaps and fostering cohesion. This approach enhances both recovery rates and stability, albeit at a higher cost, demanding specialized apparatus and technology. Conversely, the dry rock filling mining approach harnesses dry tailings, gravel, waste rock, or surface sand as fillers for gap filling. Although cost-effective, this method fails to impede surface subsidence and the infiltration of water flow.

The hydraulic slurry filling mining method retrieves coarse sand from tailings, utilizing it as a filler that is hydraulically transported to voids. This method capitalizes on pre-existing equipment and technology, but it entails substantial water resource consumption, engendering noteworthy environmental repercussions. Lastly, the paste filling mining technique amalgamates crushed tailings, water, cement, and additional constituents to generate a solidifiable paste, which is conveyed to voids via a pipeline. This approach effectively curbs surface subsidence and water flow infiltration, enhances recovery rates and stability. Nevertheless, its implementation necessitates a higher cost outlay and specialized equipment and technology.

4.2. Solid Filling Material Transportation System

Figure 6 depicts a cross-sectional portrayal of the subterranean transportation process for filling materials. In Figure 6a, the waste rock transfer machine is exhibited, while Figure 6c highlights the porous bottom unloading filling scraper conveyor, encompassing discharge orifices on each middle trough plate. The hydraulic jacks, sited on both flanks of the middle trough, govern the initiation and cessation of the discharge openings. The scraper conveyor is positioned beneath the rear top plate of the filling hydraulic support, aligned parallel to the filling working face. Additionally, Figure 6d illustrates a filling support. The transportation trajectory of filling materials unfolds through four sequential stages.

Firstly, as illustrated in Figure 6a, solid filling materials are introduced underground via the feeding orifice. Subsequently, the waste rock transfer machine facilitates the conveyance of the filling materials from the roadway to the filling working face through belt-based transportation. The filling materials are elevated to the altitude where the porous bottom unloading filling scraper conveyor is positioned. At this juncture, in Figure 6b, the filling materials transition from the waste rock transfer machine onto the porous bottom unloading filling scraper conveyor.

Continuing the process, Figure 6c marks the placement of the scraper conveyor beneath the rear top plate of the filling hydraulic support, positioned parallel to the filling working face. In alignment with the requisites for filling discharge, the scraper conveyor initiates the unsealing of the discharge aperture, subsequently expelling the filling materials behind the filling hydraulic support.

Lastly, as depicted in Figure 6d, the compaction mechanism within the filling support enacts the compression and consolidation of the filling materials within the filling area, culminating in the formation of a cohesive filler that bolsters the roof of the goaf.

This comprehensive process contributes to the establishment of a structurally enhanced roof within the goaf area, bolstered by the judicious use of filling materials and strategic transportation mechanisms.

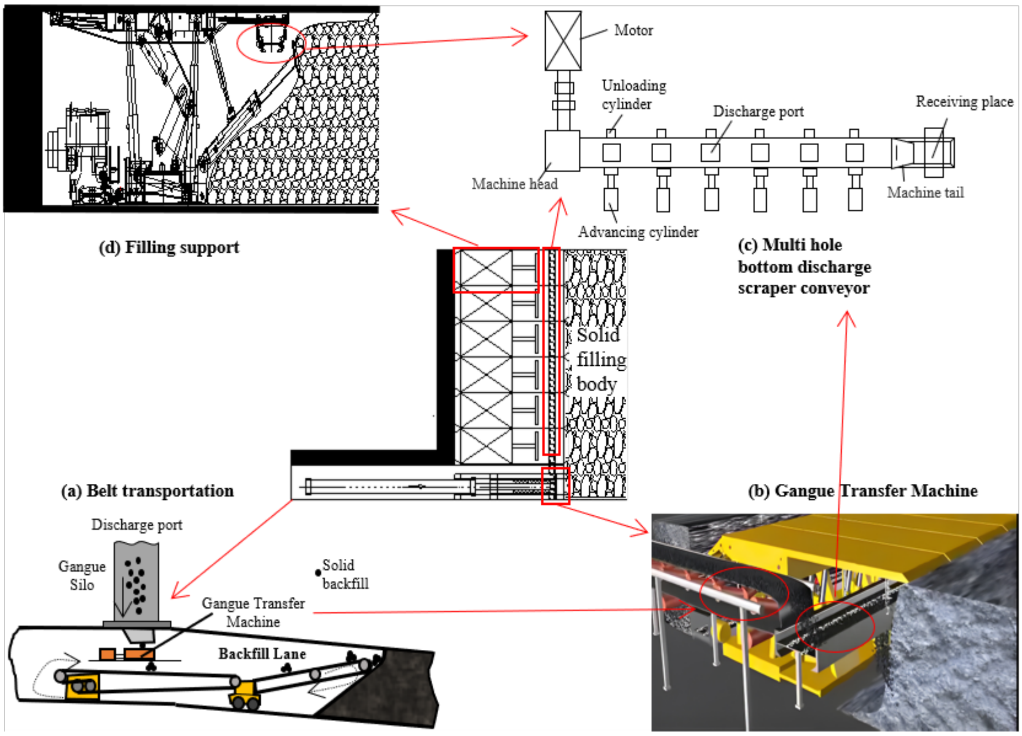

Figure 6. Coal Mine Solid Filling Transport Equipment Schematic Diagram.

4.3. Filling Actuator

According to different filling scenarios, solid filling includes solid roadway filling mining and solid working face filling mining [15].

4.3.1. Solid Roadway Filling Mining

The solid roadway filling mining technology encompasses the transportation of waste or ore generated within the mine roadway to the designated filling roadway, followed by the utilization of filling materials for its reclamation. This practice effectively curtails the volume of waste and slag within the mine roadway, thereby alleviating the environmental impact of mining activities. Furthermore, it replaces coal with waste and ore, leading to an enhanced recovery of valuable resources.

In the course of underground mining operations, waste rock is conveyed to the roadway, where a waste rock dumping machine deposits it systematically. The filling material, upon compaction, assumes a dual role: it curbs the deformation of the surrounding rock formations and establishes a robust support structure for the roof of the roadway. Consequently, stress redistribution within the rock layers of the roadway transpires, ultimately reaching a state of renewed equilibrium, all the while minimizing any adverse effects on the surface.

The solid roadway filling mining technology facilitates the direct placement of waste rock, generated during underground tunneling, into the permanent coal pillar, effectively replacing coal resources. This approach enhances resource recovery, alleviates auxiliary shaft lifting pressures, and mitigates environmental pollution stemming from waste rock. Moreover, the roadway filling system stands out for its cost-effectiveness, short-term implementation, and uncomplicated nature, rendering it a feasible filling method for mines undertaking substantial development endeavors.

For example, as outlined in Reference [59], the roadway backfilling mining (RBM) method emerged as a viable technique to curtail the disruptive impacts of coal mining on the overlying strata and safeguard water resources within the mining vicinity. This method entails the utilization of coal waste rock as the primary filling material for backfilling the subterranean goaf. In the course of the mining face's progression, a backfilling roadway is established between the return airway and the intake airway, and the backfill material is transported to the backfilling roadway via a conveyor system. Following the completion of mining face advancement, an isolation wall is erected between the return airway and the intake airway. A grouting apparatus injects cement slurry into the isolation wall, culminating in the creation of a sealed backfill structure.

This methodology significantly bolsters the stability of water resources, effectively regulates surface subsidence and fissure formation, and safeguards the stability of aquifers. The study entailed a comparison of parameters between the test area and the reference area, including factors such as surface subsidence, fissure width, and aquifer pressure. The outcomes clearly demonstrated that the degree of surface subsidence in the test area was markedly lower than that in the reference area, with a gradual reduction over time. The fissure width within the test area likewise exhibited a substantial reduction compared to the reference area, showing a correlation with increasing distance from the working face. Furthermore, the aquifer pressure in the test area demonstrated a considerable increase, demonstrating recovery over time. The permeability coefficient of the aquifer in the test area notably diminished, also showcasing a recovery trend over time. These findings collectively underscore the considerable advantages of roadway filling mining in safeguarding overlying strata and water resources.

4.3.2. Solid Filling Mining of Working Face

Solid working face filling mining technology involves the direct deposition of waste rock onto the solid working face for coal mining, facilitating concurrent support and recovery activities. This technological approach significantly diminishes the wastage of underground space and resources. It circumvents the challenges associated with waste rock disposal and treatment during coal extraction, thereby amplifying both mining safety and operational efficiency.

In the filling procedure, conveying equipment transports waste rock to the working face, where it is combined with filling materials to establish a robust structural foundation. This structure, formed from waste rock infusion, serves to fortify the roof and walls of the working face, concurrently ensuring the stability of the goaf and mitigating the risk of goaf collapse. The filling structure harmonizes with coal extraction during the working face's recovery phase, thereby accomplishing the dual objectives of support and recovery in tandem.

Illustrated in Figure 7, the filling principle diagram embodies a multi-chamber bottom unloading filling scraper conveyor positioned beneath the upper beam of the filling support. Each intermediary slot within the filling conveyor features a hydraulic discharge orifice. Waste rock descends through these apertures, subsequently undergoing compaction through the forceful action of the support's pushing and compacting mechanism. This compaction process concludes the filling operation, rendering the waste rock effectively positioned and reinforced within the structure.

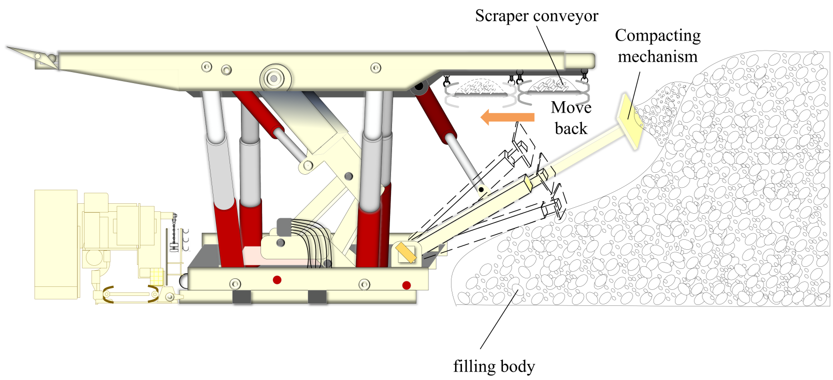

Figure 7. Solid Filling Working Face Filling Action Diagram.

The solid working face filling mining technology proves to be highly versatile, catering effectively to a diverse range of working face configurations in coal mining. This includes the fully mechanized caving face, top-coal caving face, and longwall face. This technological approach serves the dual purpose of concurrent mining and support, thereby elevating both the efficiency and safety of coal mining operations. Additionally, a notable advantage of this approach is the reduction in the treatment and discharge of subterranean waste rock, consequently contributing to broader environmental conservation initiatives.

A significant advancement in this field is highlighted in Reference [60]. This reference introduces an innovative solid working face filling mining technology tailored for steep underground coal mines. Central to this innovation is the utilization of a scraper winch system, facilitating the transport of filling materials to remote goaf areas. This technological framework not only endows the process with multiple benefits, including cost-effectiveness, minimized energy consumption, and limited environmental impact, but it also propels the concept of self-propelled filling within steep underground coal mining contexts.

The comprehensive exploration and pragmatic implementation of this technology further underscore its practical viability and efficacy. The solution proposed in Reference [60] serves as an exemplar of the potential transformation and optimization that innovative solid working face filling mining technology can bring to the coal mining sector.

5. Applicable Conditions and Application Status of Gangue Filling

Filling technology, a widely adopted approach within coal mining, plays a pivotal role in realizing efficiency, safety, and environmental sustainability throughout the mining continuum. By harnessing waste rock and filling materials, this technology effectively populates the goaf, sculpting a robust support structure that upholds stability and safety at the coal extraction front. Concurrently, it abates the specter of surface subsidence and subterranean collapse while also curtailing the generation and release of coal gangue, thus profoundly ameliorating the environmental repercussions associated with mining operations.

Moreover, the filling process engenders an upswing in coal recovery rates and maximizes the comprehensive utilization of subterranean resources. Consequently, it has evolved into an indispensable modus operandi within contemporary coal mines, making indelible marks across domains such as longwall faces, pillar filling, and beyond. Diversified materials and equipment, including waste rock dumpers, filling slurry, and fillers, contribute to the augmentation of filling efficiency and quality.

In summation, the filling procedures bear substantial ramifications within the context of coal mining. They yield robust support for efficient and secure coal extraction while concurrently elevating the eco-friendly harnessing of coal resources. The geographical distribution of solid filling technology in China is presented in Figure 8. It is evident from the illustration that the concentrations of such coal mines primarily thrive in the northern regions of China. This trend is attributed to the prevalence of coal seams beneath three layers in North China, driving heightened motivation within coal mines to embrace filling-based coal mining technology. Additionally, Table 2 delineates the application of solid waste rock filling within China. Coal mines encompassing production capacities spanning from 0.45 Mt·a^{-1} to 20 Mt·a^{-1} extensively leverage the filling technique across various provinces, signifying a widespread adoption of solid filling practices. This underscores the adaptability of filling methodologies across coal mines with divergent conditions and regional contexts, thus fortifying its standing as a versatile and efficacious technique.

Table 2. Summary of filling mines in China.

No.	Name of Mine	Capacity Mt·a^{-1}	Material	Province	Region
01	Nanyangpo Mine	0.90	Gangue	Shanxi	North China
02	Dongqu Mine	4.00	Gangue	Shanxi	North China
03	Guandi Mine	3.90	Gangue	Shanxi	North China
04	Huashengrong Mine	1.80	Gangue	Shanxi	North China
05	Dongshan Mine	1.20	Gangue	Shanxi	North China
06	Caocun Mine	0.90	Gangue and Loess	Shanxi	North China
07	Dongping Mine	1.20	Gangue and Loess	Shanxi	North China
08	Zhenchengdi Mine	1.90	Gangue	Shanxi	North China
09	Huoerxinhe Mine	4.00	Gangue	Shanxi	North China
10	Xinyuan Mine	3.00	Gangue	Shanxi	North China
11	Qianjiaying Mine	5.70	Gangue	Hebei	North China
12	Dongpang Mine	3.90	Gangue	Hebei	North China
13	Tangshan Mine	4.20	Gangue	Hebei	North China
14	Xingtai Mine	1.95	Gangue	Hebei	North China
15	Xingdong Mine	1.25	Gangue and Highwater	Hebei	North China
16	Yunjialing Mine	1.85	Gangue	Hebei	North China
17	Xinsan Mine	0.95	Gangue	Hebei	North China
18	Changcheng No.3 Mine	2.00	Gangue [1]	Inner Mongolia	North China
19	Yuxing Mine	0.60	Gangue [1]	Inner Mongolia	North China
20	Cuncaota Mine	2.40	Gangue [1]	Inner Mongolia	North China
21	QIpanjing Mine	2.40	Gangue [1]	Inner Mongolia	North China
22	Buertai Mine	20.00	Gangue [1]	Inner Mongolia	North China
23	Jining No.3 Mine	6.50	Gangue	Shandong	East China
24	Zhaizhen Mine	1.70	Gangue	Shandong	East China
25	Shengquan Mine	0.45	Gangue	Shandong	East China
26	Xiezhuang Mine	1.50	Gangue	Shandong	East China
27	Gaozhuang Mine	3.00	Gangue	Shandong	East China
28	Tangkou Mine	4.80	Gangue	Shandong	East China
29	Huafeng Mine	1.20	Gangue	Shandong	East China
30	Daxing Mine	0.40	Gangue	Shandong	East China
31	Wugou Mine	0.90	Gangue	Anhui	East China
32	Yangzhuang Mine	2.10	Gangue	Anhui	East China
33	Xuzhuang Mine	1.80	Gangue	Jiangsu	East China
34	Xingfa Mine	0.30	Gangue	Hubei	Central China
35	Zhouzhuangshan Mine	0.75	Gangue and Pastes	Hunan	Central China
36	Shier Mine	1.30	Gangue	Henan	Central china
37	Dongrong First Mine	0.90	Gangue	Heilongjiang	Northeast China
38	Xilutian Mine	2.60	Gangue	Liaoning	Northeast China
39	Xiaonan Mine	2.10	Gangue	Liaoning	Northeast China
40	Yinxing No.1 Mine	4.00	Gangue	Ningxia	Northwest China
41	Hongshiwan Mine	0.60	Gangue	Ningxia	Northwest China
42	Renjiazhuang Mine	3.60	Gangue	Ningxia	Northwest China
43	Faer No.2 Mine	0.90	Gangue [1]	Guizhou	Southwest China

[1] Plan to use.

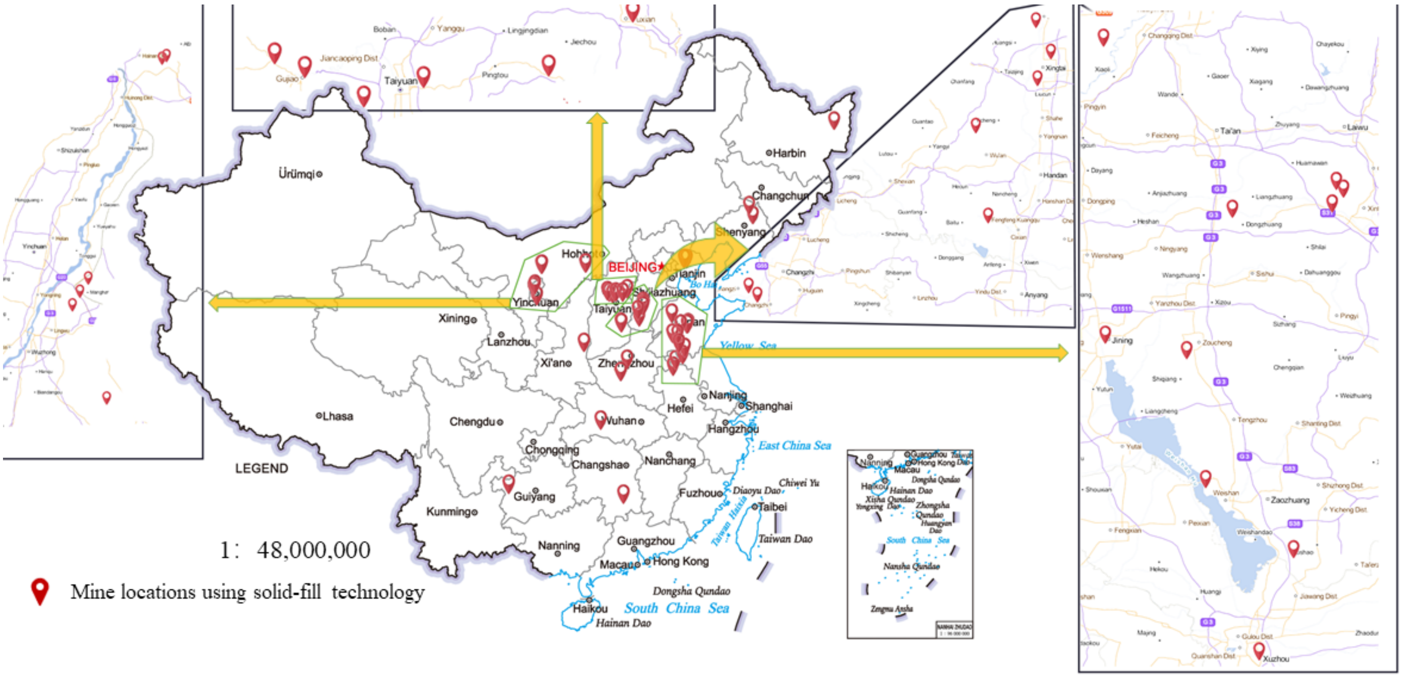

Figure 8. Distribution of mines using solid filling technology in China.

5.1. Judgment Basis of Filling Effect

The assessment of solid filling effects constitutes a pivotal process involving the evaluation and testing of the extent to which the lithological characteristics of the original goaf are reinstated within the solidly filled goaf. This meticulous procedure is imperative for upholding the safety, dependability, and stability of coal mining operations. The evaluation of filling effects is an obligatory facet in the secure and efficient implementation of solid filling technology within coal mining practices. Furthermore, it stands as a critical assurance for the proficient utilization of this technology throughout the mining continuum. The ongoing assessment and testing of solid filling effects engender a continuous refinement of both the theoretical underpinnings and practical applications of solid filling technology. This iterative process concurrently facilitates the exploration of novel solid filling technologies and methodologies, thereby offering robust support for the sustainable, efficient, and secure progression of coal mining endeavors.

The evaluation of filling quality encompasses a spectrum of factors, notably encompassing filling density, stability of the filling structure, adhesive strength, and the extent of contact surface between the filling material and the encompassing rock strata. Filling density serves as a metric that gauges the extent to which the filling material occupies the goaf, thereby ensuring the structural stability, robustness, and provision of support to the rock stratum. In addition, the adhesive strength and contact area between the filling material and the adjacent rock formation hold paramount significance, as they collectively confer the capacity upon the filling structure to effectively endure the pressures exerted by the surrounding rock. These two facets are incumbent upon meeting specific criteria to regulate roof subsidence and lateral deformation, ultimately securing the stability of the active mining front during the process of coal extraction [61].

In practical production settings, directly gauging the density and internal stress of the filling material, which serve as direct indicators of its efficacy, poses challenges. Consequently, conditions associated with the filling material, such as filling volume and roof deformation, are employed as indirect measures to ascertain its effectiveness. To this end, the concept of equivalent mining height theory has been devised as a means to gauge the filling effect through this approach.

The fundamental premise of this theory asserts that the filling material occupies a volume identical to the caving void formed by the goaf's roof. This occupation subsequently reduces the effective mining height. The actual mining height of the operational face, adjusted by the height of the compacted filling material, gives rise to the notion of equivalent mining height. By quantifying the equivalent mining height of the goaf subsequent to filling, it becomes possible to infer the compaction rate of the filling material indirectly, thereby facilitating an assessment of the filling effect. Building upon this refined theory, researchers have introduced diverse methodologies aimed at evaluating the efficacy of the filling material.

Reference [62] enhanced the model for ground pressure in the context of solid filling coal mining to analyze the mechanisms governing surface subsidence and strata movement. The study also delved into the disparities between conventional longwall coal mining and solid filling coal mining in terms of ground pressure control. In the investigation of the interplay between equivalent mining height and filling compaction rate within the realm of solid filling fully mechanized mining, Reference [63] scrutinized the impacts of filling compaction rate and mining height on the filling efficacy and surface subsidence. By aligning with the principles of solid filling fully mechanized mining, the researchers outlined the trajectory of the equivalent mining height as a function of filling compaction rate across various compaction levels. Their findings revealed a diminishing trend in the equivalent mining height with escalating filling compaction rate, with mining height exerting a pronounced influence on surface subsidence. Intriguingly, the progress of the advancing mining face led to nuanced continuous bending deformation in the overlying strata, deviating from the periodic caving failure deformation, as observed in their exploration.

In a separate inquiry, Reference [64] dissected the effects of gangue and fly ash filling compositions at varying compaction rates on the equivalent mining height. The study delved into the ramifications of these factors on strata movement control and surface subsidence in the domain of fully mechanized solid filling coal mining. The research team posited that a 15 percent filling compaction rate sufficed to maintain surface subsidence within an acceptable threshold. Lastly, Reference [65] introduced the notion of employing the filling rate as an evaluative metric for filling efficacy based on the equivalent mining height theory. The researchers converted the filling rate metric from a ratio of filling height to mining height to a ratio of filling mass to mining mass, simplifying its practical measurement on-site. Their on-field experiment endorsed the utility of the RBM (ratio of filling mass to mining mass) as a suitable and convenient direct evaluative index for gauging filling effectiveness.

Researchers have capitalized on the ubiquity of sensor technology within coal mines to analyze geotechnical stress and equipment status data collected by sensors. This data analysis enables the assessment of the filling body's condition and the effectiveness of the filling process. In a particular study [66], researchers employed vibration behavior analysis to delve into the interaction between hydraulic support and the filling body in solid filling coal mining. They introduced an approach to gauge the impact of gangue solid filling through the utilization of real-time compaction monitoring technology. By establishing a correlation model linking the compaction-forming density of the filling body to the compaction distance from the roof, grounded in the mechanism of compaction distance during on-site filling, they successfully substantiated the model's credibility through comparative experimentation.

In another investigation [67], a framework for a quality control system encompassing solid filling was postulated, and its engineering efficacy was substantiated. This system harnessed diverse sensors to amass data within the backfilling area, encompassing coal output, pressure, and stress. In real-time, the system undertook the monitoring and guidance of the filling process while concurrently evaluating its effectiveness. Empirical findings stemming from practical applications demonstrated that the researchers' proposed system framework exhibited the potential to substantially enhance the density, strength, and stability of the backfilling zone. Moreover, it succeeded in diminishing the magnitude of surface subsidence and ensuring the control of strata movement.

In an additional inquiry [68], a dynamic numerical model based on the finite element method was formulated to appraise the stability of the goaf filling body under the influence of blasting loads. This model hinged on the utilization of blasting vibration monitoring data to comprehend the status of the goaf filling body. The study showcased the model's adeptness in aligning with experimental data, effectively representing stress, strain, and displacement distribution within the filling body across distinct orientations.

Reference [69] expounds on the phenomenon of roof subsidence post backfilling, employing the continuous curved beams theory. According to this theory, the strata's behavior during filling differs from the traditional roof collapse observed in the aftermath of caving mining. Instead of precipitating fractures and through cracks, the roof metamorphoses into a coherent, continuous curved beam that retains its force-transmitting capacity even as the compaction rate of the filling material reaches 70%. Guided by this theory, the author investigates the intricate spatiotemporal interplay between roof subsidence and the compaction rate and density of the filling material. This inquiry introduces a novel paradigm for assessing the efficacy of the backfilling process.

Another seminal study [70] proposes a fresh analytical solution utilizing the differential slicing method, underpinning the formulation of a plane strain model. This comprehensive model accounts for the interplay of arching, gravity, and friction effects. The study derives analytical expressions for pertinent physical quantities, encompassing total stress, effective stress, and pore pressure within the interior and boundaries of the vertical plane filling area. This framework facilitates the evaluation of the stability of the vertically situated filling region and introduces an instability criterion to ascertain the critical strength of the laterally exposed filling body. The proposed analytical solution and instability criterion's validity and precision are verified through meticulous comparison and analysis of numerical simulations and field-acquired data. The study discerns and elucidates diverse factors influencing the stability of the laterally exposed filling body, encompassing parameters like filling height, width, inclination angle, and friction coefficient.

In another scholarly pursuit [71], a two-dimensional finite element model, Minefill-2D, is conceptualized to holistically encompass the accumulation, consolidation, cement hydration, and arching effect in the course of the filling process. Moreover, the model dynamically captures the interaction between the filling body and the enveloping rock matrix. This computational model is harnessed to simulate two goafs of varying dimensions and geometries, subsequently aligning the results with actual field-measured data. The investigation unveils the evolution of physical quantities such as total stress, effective stress, pore pressure, and seepage velocity within the interior and periphery of the goaf during the filling procedure. Of particular interest is the discernment of the arching effect's influence on the distribution of these physical quantities. Notably, the study underscores the substantial sway of the arching effect on the distribution of total stress within the filled goaf.

5.2. Typical Filling Mining Technology

Filling mining constitutes a mining methodology characterized by the amalgamation of rock or ore waste with cement and additional filling agents. Subsequently, this amalgam is injected into mine tunnels or goafs, serving the dual purpose of enhancing mine stability and ameliorating environmental contamination, while simultaneously augmenting ore recovery rates. The effectiveness and cost implications of filling mining are contingent upon the diverse mining techniques employed as well as the array of filling materials selected for the process. This section proceeds to delineate three quintessential filling mining techniques: stope filling mining, conventional filling mining, and comprehensive filling mining.

5.2.1. Roadway Filling Mining

Roadway filling mining represents a technique that entails the sequential excavation and subsequent backfilling of coal deposits. This method finds particular utility in intricate geological formations, instances of matched mining requirements, and scenarios necessitating the safeguarding of critical structures. In this process, tunneling machinery is employed for the excavation of tunnels, which are simultaneously supported during their creation. Upon tunnel excavation, the void is subsequently replenished with waste rock using a mucking machine. To optimize coal extraction while concurrently upholding the safety of protective structures, the progressive jumping mining approach can be applied.

Figure 9 presents a schematic depiction of the roadway mining procedure. During the initial phase of mining, coal pillars are typically retained to ensure the stability of the subterranean strata, albeit leading to a conservative mining rate. By incorporating the roadway filling methodology, the excavated tunnel can be filled through the use of a mucking machine following the initial mining phase. Subsequently, the second round of mining can be conducted within the now-filled tunnels using analogous techniques. Through the execution of multiple mining rounds, coupled with diligent assurance of strata stability, it becomes feasible to achieve a mining rate as high as 75%.

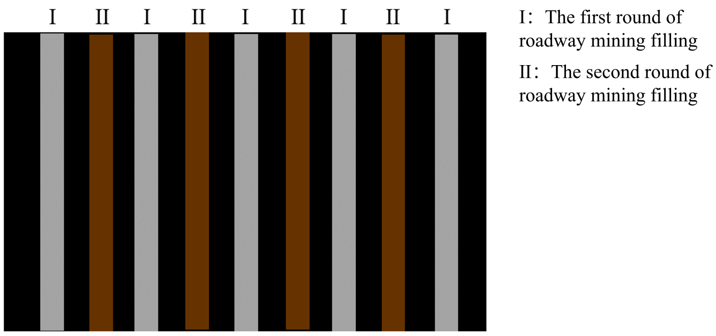

Figure 9. Roadway Filling Schematic Diagram.

Roadway filling mining is a tunnel mining method that necessitates specialized equipment, encompassing a mucking machine and a conveying system. This technique offers discernible merits, notably encompassing economical system investment, adaptable tunnel layout, diminished strata repercussions during each mining cycle, and simplified regulation of filling outcomes. Nonetheless, it is noteworthy that the yield achieved through this approach is comparatively moderate in contrast to alternative mining methodologies. Roadway filling mining finds its optimal application in regions characterized by intricate geological conditions, where safeguarding the strata holds paramount significance.

5.2.2. Conventional Filling Mining

Conventional filling mining constitutes a mining methodology characterized by the expansion of supportive space behind the coal mining face and subsequent filling of the resultant waste rock. Figure 10 elucidates the schematic layout plan of conventional filling mining, incorporating the "see six fill three" approach for roof control. Within this approach, waste rock is harnessed to fill the working face at intervals of 3 m. Upon achieving a distance of 6 m between the mining face and the filling mass, a baffle system is implemented to demarcate the coal mining face from the goaf region. Subsequently, the interior of the baffle accommodates the filling process through the utilization of a throwing machine. Throughout the filling operation, the pillars are retracted, and the filling transpires in a bottom-to-top manner.

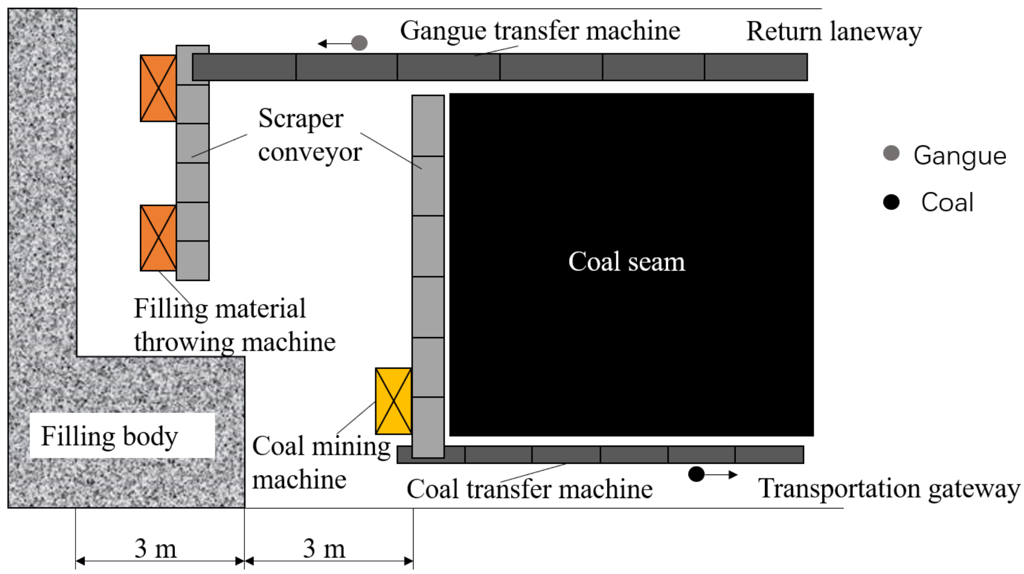

Figure 10. General Mining Filling Schematic Diagram.

The primary technical attribute of traditional filling mining resides in the practice of wall mining, which employs pivotal equipment such as throwing machines and conveying systems. This approach boasts relatively modest construction expenditures for the mining face, coupled with notably elevated production yields when compared to alternative mining methodologies. However, the effective regulation of the filling process presents a formidable challenge. Conventional filling mining finds its utility in mining scenarios necessitating comprehensive safeguarding measures.

5.2.3. Fully Mechanized Filling Mining

Fully mechanized backfill mining is a mining methodology that employs coal waste rock for goaf filling. The filling procedure adheres to the "one cut and one fill" approach, where each excavation operation provides an opportunity to backfill the goaf behind the active coal face. The overarching principle of comprehensive backfilling entails utilizing an efficient mechanized conveying system to transport waste rock from either subterranean or surface locations to the active coal face. The compaction mechanism of the hydraulic support is harnessed to propel the waste rock into the goaf, creating a cohesive filling structure. The application of fully mechanized backfill mining facilitates a high recovery rate of coal resources and the comprehensive utilization of coal waste rock. This approach has the capacity to expeditiously fill substantial quantities of coal waste rock within a condensed timeframe, harnessing the efficiency and mechanization levels of comprehensive mining machinery. Moreover, it curtails labor intensity and production expenses, bolsters production efficiency, thus representing the predominant trajectory in the advancement of backfill mining.

In reference [72], a comprehensive mechanized backfill mining process was introduced as a response to the environmental contamination stemming from the accumulation of solid waste comprising waste rock and fly ash on the surface. This innovative process integrates a self-tamping backfill mining hydraulic support, enabling concurrent coal extraction and backfilling beneath structures. The investigation integrates a range of coal mining technologies for comprehensive backfilling, encompassing the self-tamping backfill mining hydraulic support and a feeding and conveying system for the active coal face. These technologies have significantly enhanced coal recovery rates beneath structures, extended mine lifespan, and facilitated the restoration of the surrounding mining area environment.

Reference [73] delved into an extensive exploration of the research outcomes pertaining to fully mechanized backfill mining technology, with a foundation rooted in the establishment of low-carbon operational ecological mines. The investigation delved into the intricacies of managing mine pressure manifestations throughout the course of comprehensive backfill coal mining, aimed at achieving effective control of surface subsidence during coal extraction. Through the design and implementation of a robust solid backfill coal mining hydraulic support and the meticulous monitoring of coal mining pressure dynamics, improvements were realized in both coal resource recovery rates and the level of assurance concerning mine safety. These advancements culminated in surface stability assurance. This research offers invaluable insights and technical underpinning for the advancement of an ecological coal industry.

In Reference [74], the focus centered on the technical challenges associated with in situ roadway preservation along the goaf within the framework of fully mechanized backfill mining. An innovative technical blueprint was introduced, presenting a realization of roadway preservation technology along the goaf through the orchestration of coal extraction, backfilling, and roadway preservation within the temporal and spatial dimensions of the mining operation. This strategic alignment harmonizes these critical aspects, contributing to enhanced operational efficacy and safety measures.

5.3. New Filling Mining Technology

5.3.1. Mining–Separating–Filling–Retention Integrated Filling Mining

The integrated mining–separating–filling–retention approach encompasses a comprehensive fusion of coal extraction, coal gangue separation, backfilling, and roadway preservation within the mining process. Figure 11 visually depicts the conceptual representation of the integrated mining technology involving coal selection, backfilling, and roadway retention. Following the initial coal extraction, the process of coal gangue separation transpires underground. The segregated gangue is expeditiously conveyed to the backfilling working front, where it is strategically employed for goaf filling purposes. Subsequently, a systematic framework encompassing "automatic mining, subterranean gangue separation, adjacent underground backfilling, and roadway retention along the goaf" is established, thereby enabling mining without conventional pillars while ensuring the preservation of roadways.

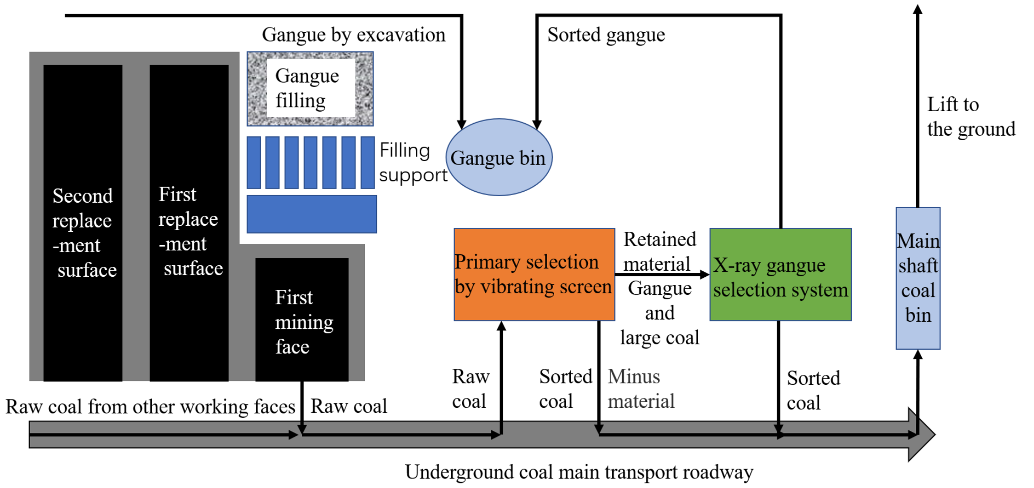

Figure 11. Mining–Separating–Backfilling–Retaining Integrated Mining Technology Diagram.

Additionally, the "coal selection and backfilling" integrated precise backfilling mining technology plays a pivotal role. This technology embodies four pivotal components: a universally applicable automatic intelligent coal mining methodology rooted in meticulous geological modeling, an X-ray intelligent coal gangue separation system adept at addressing intricate subterranean conditions, an automated backfilling mechanism facilitating on-site filling of tunneling and separated gangue, and an innovative form of roadway preservation technology along the goaf utilizing the backfill material as a supportive structure adjacent to the roadway. The collaborative integration of these technologies culminates in the realization of an efficient, intelligent, and automated mining operation, fostering safe and stable coal mining practices [75].

The concept of universal automatic intelligent coal mining technology, rooted in meticulous geological modeling, serves as an integral facet of the comprehensive mining-separating-filling-retention paradigm. This technology optimizes the fine coal extraction process through meticulous geological modeling techniques and refined mining methodologies, thereby enhancing the efficacy and safety of coal extraction. The meticulous geological modeling strategy involves the development of intricate geological and abnormal section models, utilizing supplementary exploration techniques via tunnel exploration drilling holes. By intricately modeling the coal seam's geological structure, the precision and efficiency of coal extraction receive a significant boost. The tunnel exploration drilling hole technique enriches the geological dataset, resulting in more accurate geological and abnormal section models. This, in turn, bestows stability and reliability upon the coal extraction process.

The practical realization of precise mining functions encompasses several pivotal aspects. These include the delineation of optimal cutting paths, coupled with precise positioning technology for unmanned coal extraction fronts, as well as the implementation of meticulous measurement and automated control mechanisms for backfilling support. Additionally, the technology incorporates joint surveillance of three-dimensional real-time environments and mobile video feeds. These innovations collectively foster precise positioning, streamlined path planning for coal extraction machinery and, in effect, elevate the accuracy and efficiency of coal extraction endeavors. Moreover, the meticulous measurement and automated control of backfilling support ensure meticulous backfill management, thereby upholding backfill quality and stability. The amalgamation of real-time three-dimensional scene monitoring and mobile video feeds equips the process with continuous surveillance and early warning capabilities, ultimately guaranteeing the safety and manageable execution of coal extraction activities.

The X-ray intelligent ore sorting system stands as a pivotal technological advancement, assuming a paramount role within the comprehensive mining–separating–filling–retention approach focused on coal gangue separation. Employing cutting-edge X-ray technology characterized by high efficiency, precision, and stability, this system undertakes real-time analysis and categorization of ores. This endeavor culminates in the augmentation of ore dressing efficiency and ore grade while concurrently curbing the production of coal gangue-mingled ores. Notably, the amalgamation of the ore dressing system with backfilling technology emerges as a salient hallmark of this approach.

Throughout the ore dressing process, the system meticulously segregates coal and gangue, seamlessly directing each component towards their designated areas for precise classification. Simultaneously, the remaining gangue material is expertly conveyed to the filling site and integrated using automated filling techniques, effectively circumventing the accumulation of substantial gangue quantities and attenuating potential environmental repercussions. Noteworthy in its adaptability to the intricate subterranean milieu, the system incorporates essential explosion-proof, isolation-proof, and anti-static technologies.

Distinguished by the integration of high-efficiency and steadfast X-ray analyzers alongside automated control systems, the system achieves autonomous underground operation, thereby minimizing the necessity for manual intervention. This is further supplemented by attributes encompassing rapid processing speed, pinpoint accuracy, and unwavering reliability, all of which collectively empower the system to sustain optimal performance within the rigors of the subterranean working domain.

The seamless amalgamation of mining, separation, filling, and retention stands as a pivotal linchpin in the triumph of mining endeavors. Within this holistic mining framework, the role of automated filling technology emerges as paramount, as it pertains to the immediate in situ filling of excavated mine roadways and the concurrent sorting of underground gangue. This technology proficiently segregates gangue during the coal extraction process and expeditiously fills the goaf, thus mitigating the necessity for gangue transportation and storage. Consequently, this approach culminates in reduced coal mining expenditures and abbreviated filling cycles. The orchestration of automated equipment, encompassing roadheaders, gangue reloading machinery, and filling hydraulic supports, synergistically contributes to the efficacy of this technological paradigm. Moreover, this innovation employs an intricate geological model and real-time monitoring mechanisms to supervise superincumbent rock strata, thereby assuring the dependability and stability of gangue filling endeavors.

Significantly, the technological breakthrough of employing a filling body as the supporting structure for roadway retention along the goaf holds substantial import. This method harnesses precision geological modeling methodologies to extract diverse mining parameter insights, facilitating the robust filling of gangue and the judicious preservation of roadways amid intricate geological scenarios. The mechanical attributes of the filling body along the goaf-bound roadway undergo meticulous testing and analysis, deciphering the mechanical interaction mechanisms between filling support potency and the stability of the roof's key block. Furthermore, an analysis of the stability and deformation failure patterns of the roadway support structure is undertaken, accompanied by an exploration into the evolutionary mechanics governing the near-roadway filling body across distinct mining stages.

The innovative approach of utilizing the filling body as a supportive structure for retaining roadways along the goaf stands out for its remarkable implications. This technique not only facilitates coal pillar-free mining across the entire area but also optimizes coal recovery rates while simultaneously curbing expenses. By implementing refined geological modeling during the coal extraction process, both precision and safety are elevated, ultimately leading to heightened benefits from coal mining endeavors.

The amalgamated technology encompassing coal mining and solid filling via comprehensive mechanization presents a secure and efficacious methodology for mining coal within regions situated beneath buildings, railways, and water bodies, often referred to as the "three-down" pressure coal scenario. This technology capitalizes on utilizing solid waste as a filling medium, accomplishing concurrent backfilling and support functions during the mining operation, thereby circumventing surface subsidence and environmental contamination concerns. Reference [76] systematically dissects and introduces this pioneering technology, with the objective of propelling its widespread implementation and fostering the realization of environmentally conscious mining practices within mines.

In the scholarly work outlined in reference [77], an integrated green mining technology is posited, addressing multifaceted challenges encompassing multi-level mining, surface subsidence, three-down coal resource development, and meticulous roof control. This innovative technology amalgamates coal mining, coal gangue washing and sorting, solid filling, roof control measures, and comprehensive system monitoring, synergistically enhancing the operational dynamics of mining practices.

To achieve its aims, the integrated environmentally friendly mining technology encompasses a material conveying system for joint operation between surface and underground components, an underground sorting and coal gangue processing system, a multi-tiered integrated solid backfill mining system, as well as a meticulous roof control, comprehensive monitoring, and assessment system. The approach is devised to elevate the resource recovery rate and heighten safety standards in production, concurrently leveraging subterranean low-grade coal for backfill material, thereby mitigating surface stockpiling and pollution emissions. Moreover, the technology facilitates the exploitation and utilization of "three-down" coal resources, contributing to enhanced economic returns.

The precise roof control and comprehensive monitoring and assessment system play a pivotal role in averting surface subsidence and water-related risks, thereby safeguarding the holistic ecological milieu. This technology adeptly harmonizes multi-tiered mining operations and presents effective resolutions for diverse engineering challenges.

In reference to [78], the article delves into the theory of synergy to provide insights into the concept of synergistic mining technology in deep mines, which amalgamates mining, beneficiation, and backfilling within intricate systems. The article introduces a pioneering approach to realize environmentally friendly mining practices. The paper undertook a comprehensive analysis of the distinctive attributes and benefits inherent to the integrated synergistic mining technology in the context of deep mining operations, encompassing mining, beneficiation, and filling, all within intricate systems. The article laid the foundation for a theoretical framework of synergistic mining technology, encompassing a synergistic control model, a synergistic evaluation model, and a synergistic optimization model. By devising an integrated synergistic mining approach labeled as "mining–beneficiation–filling–drainage", which prioritizes emissions reduction and waste mitigation, the authors demonstrated this methodology using a high-gas-content deep protective layer as an illustrative example, followed by on-site trials.

The outcomes unveiled the significant potential of synergistic mining technology in augmenting resource utilization efficiency, curbing energy consumption, and mitigating pollution emissions. Furthermore, the approach ensured the twin goals of safe production and a balanced ecological environment. The conducted tests definitively underscored the success of this method in generating low-carbon coal mining outputs, thereby effectively attaining the objectives of conserving energy and reducing emissions.

5.3.2. Continuous Filling Mining in the Whole Mining

Continuous backfill mining represents a mining approach characterized by the division of the mining area into discrete filling units. Within each of these units, seamless mining and backfill operations are carried out, effectively mitigating the impact of the coal seam goaf on both the surface and subsurface environments. This method achieves environmental preservation through the continuous backfilling process, thereby safeguarding the ecological balance of the surrounding mining vicinity.

The successful execution of this backfill mining methodology hinges on the availability of comprehensive backfilling equipment and cutting-edge technology, as well as the systematic planning and design encompassing the entire mining zone. In the course of mining, coal extraction is undertaken from within the coal seam, followed by direct injection of backfill material into the goaf. This process leads to the complete filling of the goaf, resulting in the formation of a robust and stabilized filling structure. Consequently, this approach realizes optimal management and utilization of goaf resources.

In accordance with [79], the application of mine filling technology is proposed as a remedial measure to address stability concerns within a large-scale stope group located in a lead–zinc mine in Inner Mongolia. The authors introduced an enhanced Mathews stability chart method that accounts for geometric parameters, surrounding rock conditions, and mining sequence of the stopes. This advanced approach enables the assessment of stability levels across each stope and facilitates the identification of those necessitating filling intervention.

Subsequently, a three-dimensional geomechanical model was meticulously constructed employing numerical simulation software FLAC3D. The primary objective of this endeavor was to dissect the ramifications of diverse filling strategies on both the stability of the collective stope and surface subsidence, subsequently culminating in the optimization of the filling approach. This analytical pursuit was then fortified through the validation of the filling efficacy via an on-site monitoring system. The findings garnered by the authors unveiled that the employed filling technology demonstrated a pronounced propensity for enhancing the stability of the stope assembly and bolstering surface subsidence management capabilities. Remarkably, the numerical simulation outcomes exhibited a commendable congruence with the empirical field monitoring data.

The ramifications of this research extend far beyond theoretical domains, possessing tangible implications for the amelioration of expansive stope assemblies. The novel methodology proposed for mine filling technology holds profound potential in addressing stability predicaments within analogous contexts, thus underscoring its intrinsic utility and broad-reaching significance.

5.3.3. Intelligent Filling Mining

Intelligent backfill mining entails the utilization of advanced automation, information, and intelligent technologies to regulate and oversee the backfill mining process. The primary objective of this technology is to enhance efficiency, safety, and dependability in backfill mining operations. The scope of intelligent backfill mining extends to various mining methodologies, encompassing solid roadway backfill mining, solid working face backfill mining, thin coal seam backfill mining, and comprehensive backfill coal mining.

The article elucidates the assortment of technologies embraced within intelligent backfill mining, incorporating diverse sensor technologies, wireless communication technology, automatic control technology, machine vision technology, data acquisition and processing technology, and artificial intelligence technology [80]. This collective array of technologies synergistically enables the autonomous management of backfill materials, real-time monitoring of backfilled roadways and filling structures, intelligent early warning and prognostication, as well as the continuous monitoring and real-time data analysis of the entirety of the backfill mining process.

The schematic representation of the intelligent solid filling hydraulic support structure depicted in Figure 12 is outfitted with an array of sensors, including angle sensors, stroke sensors, pressure sensors, material level height sensors, and cameras. These sensors collectively establish a perception network, facilitating a comprehensive understanding of the filling environment and the operational status of the filling mechanism. Subsequently, the gangue intelligent filling model utilizes the insights gleaned from the perception network to formulate filling control strategies. These strategies are contingent upon inputs from the perception network, incorporating parameters such as the stroke of the porous discharge scraper conveyor, the discharge capacity of the discharge orifice, and the angles and strokes of the pushing and compacting mechanism.

During the execution phase, the model dynamically adjusts the actions of the filling mechanism in real-time, responding to the environmental conditions and mechanism feedback as relayed by the sensors. Upon successful completion of a filling operation meeting established criteria, the data derived from the sensors, encompassing perceptions of the filling state and control of filling actions, are aggregated and disseminated. This dissemination is achieved through a fusion of decision models and a sensor network, culminating in an intelligent filling mining operation characterized by rapid responsiveness and scientifically informed adaptive decision-making.

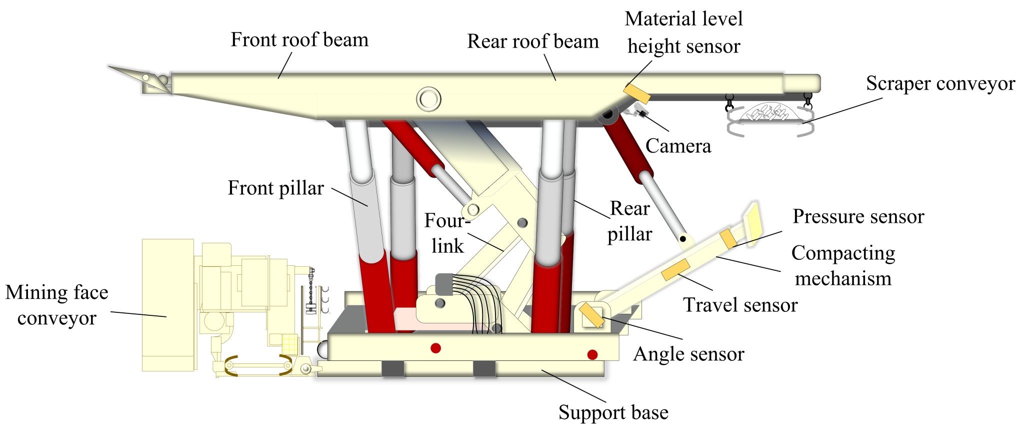

Figure 12. Intelligent Solid Filling Hydraulic Support Structure Diagram.

The implementation of intelligent backfill mining yields a multitude of advantages for the backfill mining sector. These encompass heightened production efficiency, diminished wastage of human and material resources, and an amplification of safety and dependability, culminating in the reduction of accident occurrences. Moreover, intelligent backfill mining plays a pivotal role in ensuring the stability and caliber of the backfilled material, mitigating the risks associated with collapse and cracks, consequently guaranteeing the well-being of subterranean laborers.

Reference [11] introduced an encompassing mechanized solid backfill coal mining automation system, which encompasses a comprehensive structural layout, an overarching control process, a main control system for the roadways, and a hydraulic support control system. The study put forth a series of pivotal technical control strategies and methodologies, including a harmonized operational process between coal extraction and backfilling at the coal face, an automated backfilling process for the rear end of the support, safeguarding the automatic backfilling system through the integration of a tracking function, and synchronized coordination of the shifting and backfilling scraper conveyor. The efficacy of the automation system was tested in the field, revealing a 50% reduction in backfilling time in comparison to traditional methods, significantly enhancing overall backfill efficiency.

In recent times, the integration of intelligent manufacturing technology and intelligent sensing technology has exerted a substantial influence on the evolution of solid backfill technology. Researchers have consistently endeavored to incorporate these cutting-edge technologies into backfill mining practices to foster enhanced efficiency and safety within mining operations.

In the study detailed in Reference [81], an examination was conducted into the influence of diverse 3D printed polymer structures on the dynamic splitting and crack propagation behaviors of cemented tailings backfill (CTB). This investigation employed dynamic splitting tests in conjunction with digital image correlation (DIC) techniques to evaluate the enhancements imparted by 3D printed polymer structures on multiple aspects of CTB performance, encompassing strength, toughness, deformation, and fracture modes. Furthermore, the researchers undertook an analysis of the intricate mechanisms through which 3D printed polymer structures influenced the micro-structural attributes of CTB. This analysis encompassed critical characteristics such as porosity, pore connectivity, stress wave propagation velocity, and the energy absorption capacity of CTB. Consequently, the integration of 3D printing technology offered a pioneering and effective approach to augmenting the safety and dependability of CTB within the realm of intelligent backfill mining.

In the context of Reference [82], an innovative proposal was presented, suggesting the utilization of ultrasonic measurement techniques to monitor and regulate the support function and stability of the filling body within the context of backfill mining. The researchers meticulously tracked the evolution of stiffness in cemented paste backfill (CPB) during the hydration process, delving into the influence of various factors, such as CPB specimens with varying proportions and water content. Measurements were conducted for P-wave and S-wave velocities, alongside physical properties encompassing compressive strength, density, and porosity, among others, at distinct time intervals. Experimental findings revealed a substantial correlation between ultrasonic velocity and CPB stiffness, exerting a significant impact on parameters such as hydration time, binder content, water content, and other relevant factors. As a result, researchers introduced an empirical formula grounded in ultrasonic velocity and porosity to estimate CPB stiffness.

The emergence of artificial intelligence (AI) technology has heralded a novel avenue within the realm of filling theory and technology. Researchers have adeptly harnessed the robust data processing and predictive capabilities inherent in AI technology to explore dimensions encompassing filling strategies, monitoring of filling structures, and other related domains.

In the context of [83], a notably effective and adaptable tool was introduced, facilitating the optimal design of filling structures within the purview of intelligent filling mining. The research team devised a comprehensive framework to ascertain the requisite compaction level essential for establishing stable filling bodies. This framework possesses versatile applicability, spanning diverse mining space configurations, filling structure shapes, and sizes. It also affords the flexibility to tailor influencing factors in accordance with distinct scenarios, utilizing specific parameters such as the strength of surrounding rock, initial stress, friction coefficients, among others. This systematic approach establishes rational stipulations for the strength of filling bodies contingent upon varying geological conditions and mining methodologies. The ensuing benefits encompass elevated levels of safety, operational efficiency, and economic viability within the domain of intelligent filling mining.

Reference [84] introduced a groundbreaking blockchain-driven over-limit early warning system designed for the realm of filling operations. This system encompasses critical functionalities such as equipment operation over-limit early warnings, data storage, and seamless data retrieval. The crux of this system resides in its over-limit early warning model, underpinned by the principles of transfer learning. Leveraging data generated during the operational phase of the filling system equipment, the model employs a convolutional neural network to anticipate future alterations in the equipment's operational data within a defined temporal scope. Subsequently, it detects all pertinent data, thereby pinpointing the timeline at which over-limit equipment situations might manifest in the future.

Turning attention to reference [85], the authors devised a novel approach rooted in genetic algorithms for predicting the unconfined compressive strength of cemented paste backfill (CPB). The methodology hinges on the utilization of genetic programming (GP) to establish a predictive model based on the composition and curing duration of CPB. The GP model emerges as a potent means of forecasting CPB strength, exhibiting the capacity to autonomously construct a succinct, interpretable, and scalable mathematical model devoid of the necessity for manual feature or parameter selection. Notably, the GP model showcases superior predictive performance compared to alternative machine learning techniques, boasting robust generalization capabilities and stability. This model assumes the role of an intelligent, adaptable, and efficient instrument for CPB design, yielding the potential to curtail experimental expenses and time investments while concurrently enhancing resource utilization and levels of environmental safeguarding.

Reference [86] introduced a novel approach, the random forest-factor analysis (RF-FA) data mining method, to construct a stress-strain relationship model for cemented paste backfill (CPB) under unconfined compression conditions. The study's findings demonstrated that the RF-FA model adeptly captures the stress–strain behavior of CPB across varying cement/tailings ratios, solid contents, and curing durations. Notably, the model exhibited exceptional precision and consistency. It also effectively unveiled the significance and interplay of diverse influencing variables on CPB's mechanical characteristics. This pioneering model offers a distinctive and potent avenue to harness data mining techniques, enhancing the stability and dependability of CPB in the context of intelligent filling mining.

In essence, the evolution of filling technology has been subjected to rigorous evaluation and application within the domestic coal sector, emerging as a pivotal strategy to elevate coal recovery rates, mitigate goaf issues, and ensure the geological environment's integrity. With the onward march of scientific and technological progress, coupled with the advent of innovative methodologies, filling technology is poised to ascend in significance within the coal mining landscape.

6. Problem and Challenge of Solid Filling in Coal Mine

Solid backfill mining, as an innovative and forward-looking subsurface extraction technique, is designed to realize both the safety and efficiency imperatives of coal mining operations. This approach involves the strategic deployment of waste and solid materials to effectively occupy voids, thereby providing structural support to subterranean mine cavities. Nonetheless, despite its promising prospects, the pragmatic application of solid backfill mining within coal mines introduces an intricate landscape of complexities and hurdles. These challenges span a spectrum of considerations, encompassing not only technical dimensions but also extending into the realms of economics, policy, and regulatory frameworks. The core dimensions of these challenges are articulated across six principal facets:

(1) Abundant Equipment, Elaborate Processes, and Marked Construction Extension.

The process of solid backfill mining encompasses a myriad of tasks and intricate procedures, culminating in a notable extension of the construction timeline. This procedure encapsulates pivotal facets such as the transportation of backfill materials, agitation of slurry, and reinforcement of tunneling passages. The harmonization and synthesis of these critical equipment components introduce substantial challenges, manifesting as disruptions in production and intricacies in maintenance, thus impeding the construction progression. Furthermore, the intricacy of operational workflows demands recognition. Adherence to rigorous operational protocols and vigilant oversight stands as imperative. Nevertheless, the specter of human fallibility persists, subsequently elongating the construction schedule. Furthermore, the advent of uncertainties originating from geological conditions and disparities in mine structures might mandate alterations to plans and recalibrations of equipment, thereby further elongating the overarching construction timeframe.

(2) High Material Performance Requirements, Challenges in Material Conveyance, and Precise Conveyance Demands.

The solid backfill mining procedure necessitates the utilization of materials that encompass an array of high-performance attributes, encompassing strength, stability, and adhesive qualities. These requisites are paramount to ensure the effective bolstering of underground cavities by post-backfill materials, enabling them to withstand the pressures arising from mining operations. However, attaining these requisites often involves intricate fine-tuning of material compositions and processing methodologies, thereby heightening the intricacies involved in research and preparation endeavors.

Furthermore, the transportation of backfill materials introduces notable challenges. Variability in physical properties and particle dimensions of these materials engenders significant fluctuations in their conveyance dynamics. Consequently, the conveyance of these materials becomes problematic, potentially leading to hindrances, like blockages and material seepage. Assuring the precise and consistent conveyance of backfill materials within intricate subterranean settings necessitates the deployment of sophisticated conveyance systems and real-time monitoring techniques, consequently amplifying both system intricacy and engineering expenses.

The practice of solid backfill mining mandates a stringent demand for meticulous material conveyance. The quantum and thickness of backfill material within each designated zone must be meticulously governed to warrant the stability and security of the subterranean space. However, given the intricacies inherent in backfill materials and the divergent subterranean conditions, the realization of this objective becomes progressively intricate. The evolution of intelligent control systems and precise monitoring methodologies emerges as an imperative, facilitating the attainment of precise command over the backfilling process.

(3) Process Complexity, Restricted Coal Extraction Efficiency, and Increased Coal Extraction Costs.

The process of solid backfill mining encompasses several distinct stages, spanning preparation, conveyance, backfilling, and the solidification of backfill materials. Each of these stages demands meticulous operation and stringent control measures to guarantee the quality and stability of the backfilled mass. However, this intricate process mandates a high degree of coordination, and the intricate interplay between these phases underscores that a glitch at any juncture can trigger a ripple effect, reverberating across the overall efficiency of the entire coal extraction process.

The distinctive nature of the solid backfill mining procedure can potentially impose limitations on the enhancement of coal extraction efficiency. The temporal demand introduced by the backfilling process introduces a delay into the coal extraction cycle, leading to an extension of the mining timeline and a reduction in the daily coal output of the mine. Furthermore, the requisites of preparing, conveying, and backfilling backfill materials necessitate substantial investments in terms of equipment, energy consumption, and labor allocation. Moreover, the establishment of rigorous quality control mechanisms and vigilant monitoring systems stands as imperative to ensure the steadfast stability and safety of the backfilled mass. These supplementary costs inevitably exert an influence on the broader spectrum of coal extraction expenditures, thereby attenuating the economic advantages otherwise associated with the coal mining endeavor.

(4) Challenges in Promoting Solid Backfill Mining in Small-scale Coal Mines.

Small-scale coal mining operations often grapple with inherent limitations in terms of resources and investment capabilities, which subsequently hinder their potential to embrace equipment upgrades and novel technological solutions. The assimilation of solid backfill mining technology necessitates the utilization of sophisticated backfilling equipment, efficient conveyance systems, and vigilant monitoring and control mechanisms. Regrettably, the economic landscape and financial restrictions prevalent in the context of small-scale coal mines pose significant impediments to undertaking substantial technological overhauls and equipment modernization initiatives. The inherently modest scale of operations characterizing small-scale coal mines might render certain pivotal facets integral to solid backfill mining, such as the preparation and conveyance of backfill materials, economically unfeasible to implement.

The economic feasibility of deploying solid backfill mining technology within the context of small-scale coal mines becomes susceptible to compromise. The relatively elevated upfront investment in equipment and subsequent operational costs present challenges in realizing cost reductions through economies of scale. Given the restricted resource allocation at hand, the potential advantages associated with solid backfill mining technology might not sufficiently counterbalance the financial constraints, thereby potentially impeding its seamless integration into these more diminutive coal mining enterprises.

(5) Limited Systemization and Intelligence.

Solid backfill mining, as a multifaceted subterranean extraction technique, confronts a distinctive hurdle in terms of the autonomy of its diverse components and the absence of all-encompassing integration. Across various phases encompassing backfill material preparation, conveyance, filling, and solidification, deficient coordination and amalgamation amid these stages yield incongruent production workflows and suboptimal efficiency levels. To surmount this quandary, the imperative integration of centralized control systems and intelligent technologies is evident, aiming to realize streamlined operation and adept management of the backfill mining endeavor.

Distinct phases within the realm of solid backfill mining invariably entail discrete equipment and personnel teams, engendering segmented data flow and procedural disjunction. As an illustrative instance, the formulation of backfill materials may necessitate the expertise of chemical engineers and equipment operators, whereas the actual backfilling process necessitates collaborative engagement between miners and mechanical engineers. This disjointed operational modality and information insulation can culminate in ineffectual collaborative synergy, subsequently impinging on the caliber of both production efficiency and output quality.

Moreover, the multifarious stages integral to solid backfill mining engender a requisite for meticulous synchronization to guarantee the steadiness and security of the backfilled mass. Regrettably, the absence of comprehensive cohesion spanning these stages can precipitate lagged information dissemination and feedback loops, thereby deferring issue resolution and fostering the accumulation of latent risks. This, in turn, engenders a conceivable peril to the operational safety and production stability of the coal mine. A strategic antidote to these challenges necessitates a holistic strategy encompassing centralized control systems and astute technologies, pivotal for fortifying the methodical structure and intelligent facets of the solid backfill mining process.

(6) Environmental Effects.

Traditional coal mining methods often come with severe environmental issues, such as water resource depletion, land degradation, and atmospheric pollution. These negative impacts not only constrain the sustainability of coal mining but also perpetuate continuous effects on the surrounding ecological environment. However, solid backfill mining, as a novel extraction approach, holds the potential to mitigate the environmental damage caused by traditional mining methods to some extent.

Solid backfill mining involves the efficient treatment of waste materials from the mining area, including gangue and fly ash, which are then backfilled into the goaf. This approach effectively controls strata movement and disruption, thereby reducing the extent of environmental degradation. Beyond mitigating waste accumulation, this method fundamentally addresses ecological concerns like surface subsidence resulting from goaf formation, offering a potential solution for the sustainable development of the coal mining industry.

Nonetheless, solid backfill mining is not devoid of adverse environmental impacts. Gangue in the backfill material, under prolonged exposure to acidic or alkaline mine water conditions, may release heavy metal elements, thereby heightening the risk of heavy metal contamination in groundwater. This issue is particularly pronounced when the backfill material interacts with mine water over extended periods. Nevertheless, pertinent research indicates that laying a clay layer on the floor can effectively attenuate the migration of heavy metal elements to the bottom, thereby partially alleviating this negative consequence.

In summary, solid backfill mining yields both positive and potential negative environmental impacts. While it effectively reduces the detrimental influence of coal mining on the environment, its widespread implementation necessitates a comprehensive assessment of various aspects and the adoption of corresponding measures to minimize negative consequences. This, in turn, facilitates the realization of environmentally friendly coal mining practices.

(7) Insufficient Industry Standards and Incomplete National Policies.

The lack of comprehensive standards related to solid backfill mining results in uncertainties in aspects like backfill material selection, backfilling processes, and support methods. This may lead to inconsistent approaches adopted by different coal mines in backfill mining, making it challenging to establish unified technical specifications and operational guidelines, thereby impacting extraction efficiency and quality.

Furthermore, national policies and regulations in the field of solid backfill mining require further refinement. As this extraction method differs in some aspects from traditional methods, existing regulations and policies might not comprehensively address its specific requirements. This can lead to compliance issues during actual implementation, potentially impeding the steady advancement of backfill mining.

The lack of standardization and policy support could also hinder the effective sharing and exchange of technological innovations and practical experiences within the realm of backfill mining. Without clear technical standards and policy guidance, mining enterprises might be hesitant to invest in new technologies and methods due to potential risks and uncertainties. This limitation could restrict the further development of the solid backfill mining field. To address these challenges, the establishment of comprehensive industry standards and the enhancement of policy frameworks are crucial to foster the growth and stability of solid backfill mining practices.

7. Development Trend of Solid Filling in Coal Mine

Solid filling technology can be categorized into six distinct stages based on the extent of human involvement within the filling process.

The initial stage, characterized by hydraulic sand filling, pneumatic filling in coal mining, and self-sliding filling methods employing gangue, represents a semi-mechanized approach to solid filling. Despite its application in mining regions like Xinwen, Fushun, Huainan, and Fuxin, this method exhibits a modest level of mechanization, resulting in comparatively low coal extraction efficiency, elevated operational costs, and a notable scarcity of suitable filling materials.

Progressing to the second stage, we encounter mechanized solid filling, which encompasses techniques such as gangue tossing filling, original gangue integrated mining framework backfilling, and roadway filling. This stage signifies a significant enhancement in mechanized filling coal mining efficiency and mechanization standards. Its successful implementation can be observed in mining locales like Xingtai, Xinwen, Yanzhou, and Zaozhuang. Nonetheless, challenges persist in terms of achieving optimal filling density and effectively controlling strata movement.

The third stage introduces comprehensive mechanized solid filling, a pioneering approach that merges the capabilities of comprehensive mechanized coal mining fronts with mechanized solid filling equipment systems. This integration enables the simultaneous execution of coal extraction and filling operations. Notably employed in Xingtai Coal Mine, this stage employs high-density filling to effectively manage strata movement. However, this stage presents intricate processes, lower filling efficiency, and heightened labor demands for workers.

The fourth stage encompasses automated solid backfilling, entailing automation features like bidirectional transportation within the main shaft, gangue classification, conveyance mechanisms, overarching control systems, and support control mechanisms. This phase attains automation control over the backfilling process, effectively diminishing the labor-intensive nature of manual labor. Notably, this approach has been successfully implemented in Xingdong Mine. However, a notable gap exists in the form of a scientific and objective evaluation system and methodology for assessing backfilling efficacy. As a result, achieving fully unmanned operations at the active coal face remains an elusive goal.

The fifth stage revolves around the integration of "mining–selection–filling–retention." This integrative approach involves the exploration of intelligent sorting below ground, in situ backfilling techniques, and a multi-process collaborative intelligent control system within coal mines. The independent operation of distinct systems is a focal point, yet human intervention remains essential for evaluating backfilling outcomes and devising control strategies. As of now, the comprehensive research framework and equipment infrastructure for intelligent underground sorting and in situ backfilling technology have been established, with active implementation already initiated in Zhaizhen Coal Mine.

The sixth and final stage entails intelligent solid backfilling, centering on aspects like the composition ratio of intelligent materials, the development of a refined geological model for the backfill working face, and the establishment of an intelligent control system. Pertinent research endeavors have laid the groundwork for the technical framework and route of intelligent mining, leading to the creation of various intelligent tools. However, specific intelligent methodologies and control techniques are still in the research and development stage.

The application of filling technology in coal mining necessitates the fulfillment of specific prerequisites. Primarily, a sufficient supply of appropriate filling materials such as tailings, coal gangue, and slag must be accessible. Equally important is the existence of a suitable filling process capable of amalgamating these materials with the coal seam, thereby engendering a robust and stable support structure. Moreover, the presence of adept technical support and qualified personnel is imperative to oversee the technology's implementation, thereby guaranteeing the efficiency and safety of the filling endeavors.

Furthermore, the prerequisites for deploying filling technology can vary in correspondence with distinct coal seam types. For example, the extraction of thin coal seams demands distinct filling materials and processes, tailored to the nuances of their specific conditions. Similarly, coal seams characterized by high ground stress necessitate an all-encompassing geological appraisal and stress analysis prior to filling, mitigating the risk of geological upheavals post-filling. Consequently, when leveraging filling technology for coal mining pursuits, the formulation of scientifically sound and contextually appropriate filling strategies and technical protocols is paramount to ensure the seamless advancement of filling operations.

Nonetheless, challenges arise during the filling process, including:

Primarily, the selection and composition of backfill materials necessitate meticulous consideration of diverse factors encompassing goaf geology, backfill objectives, and environmental preservation. The task of identifying suitable backfill materials and refining their proportions represents a pivotal quandary within the realm of backfill technology.

Secondly, the monitoring and regulation of backfill quality and deformation throughout the backfilling process stand as pivotal safeguards to uphold backfill excellence and safety. Nonetheless, conventional methodologies are riddled with challenges like untimely monitoring, imprecise data, and a dearth of real-time feedback mechanisms. Pioneering the evolution of advanced monitoring and control technologies tailored for real-time supervision of backfill quality assumes paramount significance in elevating backfill safety.

Thirdly, the judicious selection and deployment of backfill processes and equipment wield substantial influence over backfill quality and efficiency within the backfilling endeavor. However, time-honored techniques are plagued by complexities in operation, inefficiency, and excessive energy consumption, rendering them inadequate for large-scale backfilling requisites. Pioneering innovative and streamlined backfill processes and equipment represents an imperative in augmenting backfill efficiency and quality, thereby addressing the developmental challenges facing backfill technology.

In synopsis, solid backfill technology emerges as a foundational resolution for the adept management and utilization of goaf resources within the coal mining sector, notwithstanding the multifaceted technical hurdles that confront it. As the trajectory unfolds, scholarly endeavors should center on novel frontiers such as investigating innovative backfill materials and proportioning methodologies, optimizing monitoring and control frameworks, enhancing backfill processes and equipment, and bolstering the management of backfill safety. This concerted research focus is poised to amplify the effectiveness, quality, and security of solid backfill technology implementation within coal mining operations.

7.1. New Solid Filling Material

In the dynamic landscape of technology's continuous progression and development, the exploration and application of novel materials have garnered extensive attention and widespread endorsement. Within the realm of solid backfilling within coal mines, the trajectories of new solid backfilling materials' evolution are outlined as follows.

A pivotal avenue of development entails the utilization of industrial byproducts and household refuse as foundational constituents for the composition of solid backfilling materials. This strategic approach yields multifaceted benefits, encompassing the reduction of waste disposal expenditures, the mitigation of environmental degradation, and the conservation of resources within the backfilling materials domain. Notably, Reference [35] spearheaded the creation of an innovative backfilling material through the repurposing of discarded steel slag as a foundational component. This endeavor not only facilitated the efficacious utilization of abandoned steel slag resources but also yielded an enhancement in the performance attributes of the novel backfilling material. Similarly, Reference [87] harnessed a composite cementitious material derived from fly ash, slag, and other elements, serving as a potent mine filling binder. This distinctive formulation consisted of constituents such as municipal solid waste incineration fly ash, steel slag, blast furnace slag, and desulfurized gypsum. The cementitious amalgamation adeptly solidified tailings, curtailed the potential leaching risks associated with heavy metals and dioxins, and effectuated efficient waste repurposing, embodying an exemplary demonstration of waste-to-value transformation.

Cognizant of the ongoing quest for sustainable practices, the incorporation of discarded materials into functional backfilling agents resonates with the overarching aspiration for resource efficiency and environmental responsibility. These innovative strides showcased in the references mentioned fortify the arsenal of methodologies available to drive responsible and effective mining practices.

Another noteworthy trajectory of development involves the enhancement of solid backfilling material performance through the incorporation of chemical additives. Through the judicious introduction of suitable chemical additives, the strength and stability of solid backfilling materials can be augmented. Reference [38] undertook a comprehensive study where industrial graphite oxide/fly ash was integrated as a chemical additive to augment the mechanical attributes and permeability of backfilling materials, concurrently reducing the consumption of cement. Additionally, findings from a study conducted by Reference [39] highlighted that the integration of polypropylene fibers into solid backfilling materials led to amplified crack resistance and ductility, ultimately culminating in heightened mechanical strength during advanced stages.

Furthermore, the adoption of biotechnology to enhance the ecological compatibility of solid backfilling materials constitutes a significant trajectory. This strategy is geared towards ameliorating the adverse environmental impacts associated with solid backfilling materials on soil and groundwater. In the research presented by Reference [40], the application of Bacillus subtilis, a robust strain, was introduced to facilitate carbonate precipitation within solid backfilling materials. This approach also advocated the formulation of gangue-based filling materials underpinned by biomineralization principles. Through biomineralization, the microcrystalline framework of backfilling materials underwent transformation, resulting in heightened structural stability and resistance to erosion. Furthermore, this preparation process led to a reduction in cement usage, effectively curbing its ecological footprint.

In summary, the contemporary evolution within the domain of coal mining solid backfilling materials encompasses a series of progressive trends. These trends encompass the integration of industrial waste and domestic refuse, the incorporation of chemical additives, and the harnessing of biotechnological interventions. Beyond their capacity to elevate the efficacy and steadfastness of solid backfilling materials, these trends bear the promise of curbing environmental repercussions. Consequently, they usher in fresh avenues and prospects for the advancement and implementation of coal mining solid backfilling technology.

7.2. Intelligent Monitoring and Control Technology

Intelligent monitoring and control technology encompass the application of cutting-edge scientific and technological methodologies, including digitization, standardization, and networking, to attain real-time data collection, analysis, processing, and responsive adjustments across multiple phases of the backfilling process. This integrated approach significantly elevates the efficiency and efficacy of the backfilling procedure [88]. This technology assumes a pivotal role in the subsequent domains:

7.2.1. Intelligent Detection and Analysis of Backfilling Materials

The intelligent assessment and analysis of backfill materials incorporate cutting-edge technologies, such as sensors, image processing, and data mining, to enhance both the quality and efficiency of backfill material utilization.

Intelligent sensor technology facilitates the real-time monitoring of critical parameters, including temperature, pressure, humidity, and pH levels of backfill materials, as depicted in Figure 13. These sensors swiftly and accurately capture the physical characteristics of the materials, transmitting this data to a centralized control system for comprehensive analysis. By scrutinizing this live data, any anomalies are swiftly identified, enabling corresponding adjustments to be implemented promptly. This proactive approach ensures the consistency and stability of the backfill materials.

The role of image processing technology is pivotal in the intelligent assessment and analysis of backfill materials. Through the integration of image sensors and sophisticated computer vision algorithms, contactless detection and analysis of surface topography, particle distribution, and pore structure of the backfill materials can be achieved. This culminates in the processing and interpretation of image data to provide invaluable insights into particle size distribution, porosity, and particle interactions within the backfill materials. These insights are crucial for refining mixture ratios, optimizing the backfilling process, and evaluating the overall performance of the backfilled mass. Furthermore, image processing technology elevates non-contact detection and analysis capabilities related to surface morphology, particle distribution, and pore structure of the backfill materials. By employing image sensors and advanced computer vision algorithms, image data can be gathered and processed, offering vital information regarding particle size distribution, porosity, and particle interactions. Such information serves as a cornerstone for fine-tuning mixture ratios, streamlining the backfilling procedure, and assessing the effectiveness of the backfilled mass. Data mining techniques exhibit a broad spectrum of applications in the realm of intelligent detection and analysis of backfill materials. This encompasses the compilation and integration of an extensive corpus of data pertinent to backfill materials, encompassing process parameters, real-time monitoring data, and historical records. By harnessing data mining algorithms, these datasets undergo scrutiny and exploration, facilitating the discovery of concealed patterns, trends, and interrelations. As a result, intrinsic insights and predictive models pertaining to the traits and performance of backfill materials emerge. These models serve as pivotal components in furnishing decision-making support for the optimization of mixture proportions, process augmentation, and the assurance of quality control over backfill materials.

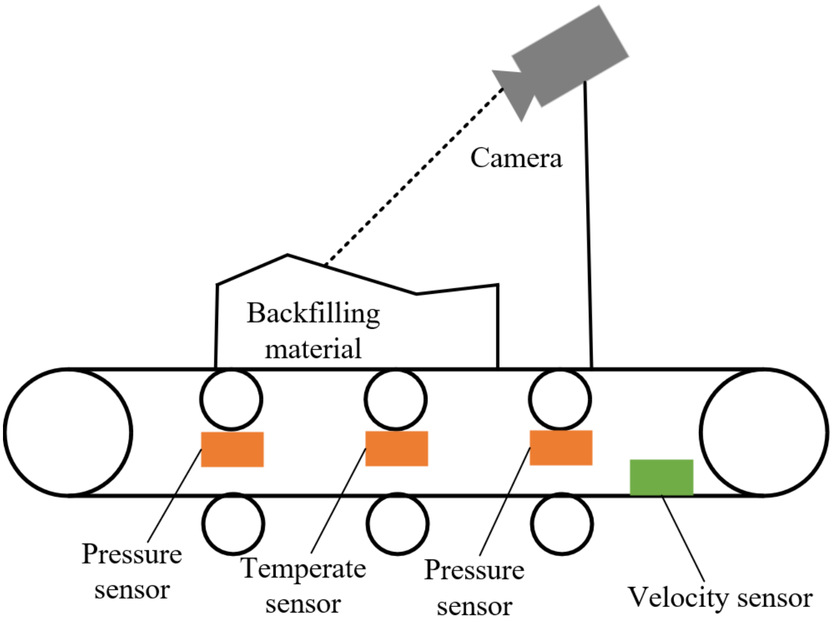

Figure 13. Intelligent detection and analysis system for backfilling materials.

The application of intelligent detection and analysis to backfill materials empowers the domain of solid backfilling in coal mining to attain meticulous regulation and refinement of material caliber. Concurrent real-time and offline monitoring and analysis expedite the swift identification of potential concerns, thereby enabling the prompt deployment of requisite countermeasures to ameliorate the quality and utilization efficacy of backfill materials.

7.2.2. Intelligent Monitoring and Early Warning in the Backfilling Process

Intelligent monitoring and preemptive alert systems in the context of backfilling represent pivotal directions for future advancements within the domain of solid backfilling within coal mining. By integrating cutting-edge monitoring technologies and intelligent systems, the attainment of real-time monitoring, data analysis, and anomaly detection is feasible. This amalgamation bears the potential to significantly elevate the safety, stability, and efficiency of backfilled masses.

The architecture of an intelligent monitoring system can encompass an array of sensors, collectively yielding real-time data on pivotal parameters throughout the backfilling procedure. To illustrate, pressure sensors can be harnessed to oversee the exerted forces and subsequent reactions of the backfilled mass on the encompassing rock strata. Employing a repertoire of devices, including velocity sensors, pressure sensors, laser scanners, and cameras, facilitates the continuous real-time evaluation of the state of the backfill materials upon conveyor belts and scraper conveyors. Through this mechanism, indicators such as mass flow rate, volume flow rate, and material density of the backfill materials can be promptly tracked. This proactive monitoring strategy promptly detects potential transportation glitches and provides oversight of the feed rate at the active coal face. The strategic deployment of this intelligent monitoring technology serves as credible evidence for the timely anticipation and identification of potential risks linked to roof collapse, thus enabling the prompt implementation of support and safety protocols [89]. Accurate oversight and management of the backfill material transportation process not only ensure a consistent supply and stability but also result in an elevated level of backfilling efficiency, concomitantly curbing transportation-associated risks [90].

An intelligent monitoring system can perform real-time analysis and exploration of large volumes of data generated during the backfilling process through data analysis and processing. Utilizing technologies such as machine learning, data mining, and artificial intelligence, anomalies, trend changes, and potential risks during the backfilling process can be identified. The system can compare real-time data with historical data and employ preset algorithms and models for real-time analysis, monitoring the equipment status during the backfilling process, and promptly handling any abnormal situations. For example, by identifying and monitoring the support position and mechanism interference of roof supports, the system can promptly detect support deformation, instability, or other abnormal conditions. This intelligent monitoring and control technology is crucial for ensuring the stability and effectiveness of roof supports. By monitoring the posture of the supports in real time, the system can provide warning information to facilitate timely adjustments and maintenance measures, ensuring the safe operation of supports during the backfilling process.

An intelligent monitoring system can provide timely warning and alarm functions. This enables coal mine managers and workers to take timely measures to avoid potential safety risks and losses. Once the system detects anomalies during the backfilling process, such as excessive pressure, abnormal displacement, or elevated temperature, it automatically triggers the warning mechanism and sends alert notifications to relevant personnel. Lastly, this ensures that the system is able to provide timely warning and alarm functions, allowing for quick response and mitigation of potential safety hazards.

An intelligent monitoring system assumes a pivotal role in effectuating real-time analysis and exploration of substantial data volumes generated throughout the backfilling process, employing data analysis and processing methodologies. By harnessing cutting-edge technologies encompassing machine learning, data mining, and artificial intelligence, the system is proficient in identifying anomalies, discerning shifts in trends, and pinpointing potential risks intrinsic to the backfilling operation. This analytical prowess extends to the juxtaposition of contemporaneous data against historical records, leveraging preconfigured algorithms and models to execute real-time assessments. The system vigilantly oversees the operational status of equipment throughout the backfilling endeavor, adeptly addressing any aberrant scenarios that might transpire. For instance, by vigilantly tracking support positions and detecting potential interference in the mechanism of roof supports, the system stands poised to promptly detect deformations, instability, or any untoward occurrences. This intelligent monitoring and control technology bear paramount significance in safeguarding the stability and efficacy of roof supports. By perpetually surveilling support configurations in real time, the system offers preemptive alerts, facilitating prompt adjustments and maintenance interventions to ensure the secure operation of supports during the backfilling process.

Moreover, the intelligence imbued within the monitoring system equips it with the capability to issue timely warnings and sound alarms. This proficiency empowers coal mine management and workforce personnel to expediently instigate mitigative measures, averting potential safety hazards and minimizing losses. Upon detecting anomalies in the backfilling process—such as excessive pressure, anomalous displacement, or heightened temperatures—the system promptly triggers its warning mechanism, propelling alert notifications to pertinent staff members. Ultimately, this dynamic functionality ascertains the system's efficacy in delivering punctual warning and alarm functions, precipitating swift responses and the attenuation of potential safety perils.

7.2.3. Intelligent Determination and Evaluation of Backfilling Effect

Solid backfilling within coal mines constitutes a method employing both coal mine waste and materials like cement to infill the goaf region. This practice yields enhancements in coal retrieval efficiency and safety. The intelligent assessment and appraisal of backfilling outcomes emerge as a pivotal subject within the domain of solid backfilling in coal mines. This entails the consideration of a spectrum of factors, encompassing the performance attributes of backfilling materials, process parameters, and the enduring stability post-backfilling.

To propel the progression of solid backfilling practices in coal mines, forthcoming research and applications can be strategically channeled into the subsequent focal areas:

Amidst the rapid evolution of Internet of Things (IoT) technology, the attainment of real-time monitoring for pivotal parameters during the backfilling process is achievable through the integration of sensors and monitoring devices into the network. This integration is facilitated by cutting-edge technologies including big data analysis and cloud computing. These advancements empower the storage, processing, and analysis of substantial backfilling datasets, thereby elevating the precision and visual representation of backfilling outcomes. As a result, real-time monitoring and early warning capacities for backfilling projects can undergo enhancement, accompanied by a heightened level of granularity in data analysis and decision-making support for optimization endeavors.

Throughout the backfilling process, an assortment of sensors, such as pressure sensors, temperature sensors, and humidity sensors, is conventionally employed for data collection. By harnessing the potential of IoT and big data technologies, the fusion of multi-sensor data can be seamlessly executed, effectively amalgamating and scrutinizing data originating from diverse sensor sources. This integration facilitates a comprehensive and precise depiction of the backfilling environment, along with discernment regarding the movement and orientation of the backfilling equipment. This, in turn, establishes a more refined bedrock for intelligent optimization control.

Furthermore, image data procured throughout the backfilling procedure hold invaluable insights pertaining to the allocation of backfilling materials and the condition of supporting structures. To process and decode this image data, machine learning methodologies including deep learning and convolutional neural networks can be harnessed. These approaches empower preprocessing, enhancement, segmentation, and other operations on the images, culminating in the augmentation of their quality and lucidity. Beyond this, they expedite the automated identification of target areas and anomalies within the images, thus contributing enhanced precision in data underpinning the evaluation of backfilling quality.

Intelligent assessment models for gauging the impact of backfilling can be devised through the incorporation of artificial intelligence (AI) and machine learning (ML) technologies. These models have the potential to realize automated and intelligent determinations of backfilling efficacy by extrapolating crucial features and influential factors via data mining and knowledge exploration, drawing upon historical records and real-time monitoring data. Such an approach promises precise evaluations and predictive capabilities, thereby advancing the refinement of backfilling strategies and the enhancement of their effectiveness.

For instance, machine learning methodologies encompassing clustering, classification, and regression algorithms can meticulously sift through extensive backfilling datasets. By autonomously assimilating and identifying pivotal features and patterns during the backfilling process, this approach facilitates the formulation of accurate mathematical models and evaluation metrics. This data-centric analytical approach underpins an all-encompassing and impartial assessment of backfilling quality.

Furthermore, the realm of artificial intelligence can contribute to intelligent backfilling optimization and control. Techniques like reinforcement learning and genetic algorithms can be harnessed to enable machine learning systems to independently adapt backfilling parameters and tactics in response to real-time feedback. This adaptive modus operandi leads to the optimization of the backfilling procedure and its outcomes, thereby attaining responsive control. This intelligent optimization and control mechanism notably heightens backfilling efficiency, curtails energy consumption, and ensures the steadfastness and uniformity of backfilling quality.

Simulation platforms for assessing backfilling efficacy can be established by leveraging cutting-edge technologies such as virtual reality, augmented reality, and digital twins. These platforms serve as arenas for validating and optimizing backfilling strategies. By simulating the backfilling process and its outcomes, it becomes possible to forecast and regulate backfilling effects. This simulation-based approach not only curtails the expenses and hazards associated with physical experiments but also furnishes engineers and decision-makers with a virtual experimental milieu.

Furthermore, visualizing the consequences of backfilling operations facilitates enhanced comprehension and assessment of the viability and potency of these strategies. Ultimately, this engenders the availability of comprehensive and dependable data that informs the planning and decision-making underpinning backfilling endeavors.

The trajectory of solid backfilling initiatives in coal mines is poised for heightened efficiency, safety, and sustainability. This trajectory will be steered by the persistent integration and deployment of intelligent monitoring and control technologies. Such advancements will supply the requisite technical backbone and decision-making benchmarks for the pragmatic execution of backfilling undertakings. By doing so, they will not only foster ongoing research and development within this domain but also catalyze its broader adoption and application.

8. Conclusions

Having undertaken a comprehensive analysis of the advancements in China's research pertaining to solid backfilling in coal mining, we have not only synthesized notable accomplishments but also engaged in a thorough contemplation of the prevailing challenges. This rigorous assessment has, in turn, catalyzed a more profound introspection into the realm of integrated solid backfill mining.

First and foremost, within the framework of technological progression, China's solid backfilling technology within the coal mining sector has exhibited a progressive trajectory. Nonetheless, it remains imperative to acknowledge that several unexplored domains warrant concerted investigation. Notably, in the realm of solid backfilling materials, the pursuit of more ecologically sustainable alternatives remains an unresolved quandary. Striking the delicate balance between material costs and performance metrics necessitates further extensive inquiry.

Moreover, in the context of amalgamating mining operations with backfilling endeavors, the optimization of mining processes to harmonize with the application of backfilling technology, alongside the efficient recuperation of backfill materials, presents domains ripe for further empirical exploration and innovative interventions.

As we cast our gaze both retrospectively and forward, our assessment of prevailing perceptions and practices in solid backfilling technology underscores a distinct milestone in this journey. Projecting our vision towards the future mandates an unwavering commitment to incessant innovation and research, driving the frontiers of technology to ever-expansive horizons. Our canvas of opportunities unfurls across domains like pioneering materials, intelligent control mechanisms, and the realm of machine learning. Parallelly, our attention must remain attuned to the ecological and societal repercussions inherent in solid backfill mining. Concomitant with technological leaps, proactive mitigation of potential adverse outcomes becomes paramount, guiding our trajectory toward a sustainable developmental paradigm.

In forthcoming research odysseys, the potency of interdisciplinary collaboration emerges as a cornerstone. Converging with luminaries hailing from geotechnical engineering, environmental sciences, mechanical engineering, and allied domains promises to usher in a tapestry of innovative outlooks and solutions in the landscape of solid backfill mining. Likewise, a panoramic cognizance of global trends in solid backfilling technology is indispensable. By assimilating insights gleaned from the experiences of other nations, we enrich our repository for the perpetual augmentation of China's solid backfilling technology.

In summation, this discourse has charted a course through the annals of China's solid backfilling technology within the coal mining domain, simultaneously plumbing the depths of introspection and casting the spotlight on forthcoming considerations. We envisage that, through the forthcoming trajectory, solid backfilling technology will not solely surmount challenges and drive innovation, but will also etch substantial contributions into the annals of sustainable advancement within the coal mining industry.

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