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Invited Review

Systematic review of mixing technology for recycling waste tailings as cemented paste backfill in mines in China

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Abstract: The development of industry is inseparable from the support of mining. However, mining processes consume a large amount of energy, and increased tailing emissions can have a significant impact on the environment. In the past few decades, the mining industry developed many technologies that are related to mineral energy management, of which cemented paste backfill (CPB) is one of the representative technologies. CPB has been successfully applied to mine ground control and tailings management. In CPB technology, the mixing process is the key to achieving materials with good final quality and controlled properties. However, in the preparation process, the mixed homogeneity of the CPB is difficult to achieve because of fine tailings, high solid volume fraction, and high viscosity. Most research focused on the effect of mixing ingredients on CPB properties rather than on the preparation process of the CPB. Therefore, improving the performance and reducing the production cost of CPB by optimizing the mixing process are important. This review summarizes the current studies on the mixing technology of CPB and its application status in China. Then, it compares the advantages and disadvantages of multiple mixing equipment and discusses the latest results and research hotspots in paste preparation. Finally, it concludes the challenges and development trends of mixing technology on the basis of the relevant application cases in China to promoting cement-based material mixing technology development.

Keywords: cemented paste backfill; mixed homogeneity; mixing technology; cement-based material

1. Introduction

Currently, mining is playing an increasingly prominent role in global economic and social development. In China, the mining industry has always been one of the important pillars of the national economy [1–2]. The development of mineral resources has promoted China's economic and social development. However, behind the booming economy is the accumulation of many tailings on the surface (Fig. 1(a)) and a large quantity of goaf left underground [3–4]. The mining industry is definitely responsible for high energy consumption and excess pollution. As the Chinese government gives high priority to green development, the environmental management of mining will become an inevitable choice.

Statistics show that the accumulation of tailings in China has reached 14.6 billion tonnes, the volume of goaf has totaled more than 25 billion m^3, and the annual water resources polluted by mining (Fig. 1(b)) [5] are 2.4 billion m^3, which confirms that the mining industry seriously damages the ecological environment and pollutes water bodies [6]. Furthermore, tailing ponds are highly prone to tailing dam breaks, which often cause serious accidents. For example, tailing dam breaks in Shanxi Province (China) in 2007 and Brumadinho (Brazil) in 2018 caused 277 and 254 deaths, respectively [7]. Moreover, surface collapses often occur in underground goaf (Fig. 1(c)). In 2017, goaf falls and collapse caused 140 deaths in China. Therefore, the ecological construction of mines has become an important issue for the mining industry.

Cemented paste backfill (CPB) technology has been widely adopted in China to minimize severe environmental damage and safety problems faced by China's mining development. In this manner, green metal mining becomes possible. CPB is a paste prepared by mixing solid mine waste (tailings, coal gangue) with cement, which can realize 100% utilization of tailings [8]. It achieves resource utilization of solid waste in mines and solves the environmental and safety problems of tailings storage facilities (TSFs) and goaf, i.e., to dispose of two primary dangerous sources in mines (TSFs and goaf) with only one type of hazardous waste [9–10].

The application of CPB technology covers three major processes: tailing concentration, mixing preparation, and

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Fig. 1. Tailing accumulation (a), water pollution (b) [5], and surface collapse (c) of mining.

pipeline transportation, of which the mixing preparation is the important step. Its purpose is to disperse, wet, and homogenize cementitious materials, tailings, and additives to form a stable paste that is easy to convey. The CPB mixture has achieved the transformation from slurry to paste [11]. The effect of mixing on paste properties is often overlooked [12]. However, many studies demonstrated that mixing changes CPB's rheology, hydration, and hardening mechanical properties [13]. Therefore, mixing research is important to improve the theory of paste backfill and its promotion and application. By summarizing the current application status and development prospects of CPB mixing technology in China, this review hopes to promote the better development of paste backfill technology.

2. Methodology

This review primarily uses the China National Knowledge Internet (CNKI) to search for related works of literature in the Chinese Science Citation Database (CSCD). It uses the literature published by the Science Citation Index (SCI). This article analyzes the published scientific literature in the field of CPB of mines from 2000 to 2022, mostly focusing on colliery, paste backfilling, numerical simulation, and mixing preparation. By analyzing 534 English papers and 623 Chinese papers retrieved from CNKI and SCI, respectively, we report that CPB has been increasingly applied in China since the twentieth century. Most studies focus on the tailing concentration and transportation of CPB; however, there is little research on CPB mixing technology.

After analyzing titles and abstracts, we first screened related literature, roughly reviewed the content, and featured >200 documents. The research status quo of CPB mixing technology is summarized through a detailed analysis of 122 of these works. Certain representative cases are listed in this review to compare the performance, advantages, and disadvantages of different mixing equipment, and the mixing mechanism of CPB is introduced in detail. Moreover, this review analyzes the prospects of CPB hybrid technology and summarizes the challenges and personal insights of CPB hybrid technology. Hopefully, this work will popularize the development of CPB.

3. Mixing technology for cemented paste backfill in metal mines

3.1. Cemented paste backfill technology

CPB technology involves mixing unclassified tailings with cementitious materials and water to form a toothpaste-like slurry with stability, fluidity, and plasticity [14–16]. The concrete steps are as follows: full tailings slurry that has not been dewatered from the concentrator is pumped to a deep cone thickener [17] in which the slurry is gravity-dewatered and concentrated (flocculants are usually added during this process to accelerate fine particle sedimentation). The high-concentration slurry is then pumped into the mixer and mixed with cemented material to prepare a paste. The fresh paste that meets the transportation requirements will be transported to the goaf area via a pump or gravity. CPB technology not only reduces the volume of tailings but also eliminates the requirement to build surface tailing ponds, thus significantly protecting the environment.

3.2. Development of paste technology in China

CPB originated in the 1970s. Preussag Metal, a company in west Germany, performed the first backfilling experiment with cemented paste at the Bad Grund lead-zinc mine in 1980 and succeeded after six years of research [18]. Since then, the CPB has been rapidly growing all over the world.

For decades, China has been using conventional concrete cement filling to dispose of tailings [19], which is a complicated, expensive, and inefficient process. With the development of CPB, the mining industry in China has become aware of its good performance, as shown in Fig. 2. In the 1990s, Jinchuan Group Co., Ltd. planned to establish the first CPB test system in China [20]; in 1996, the first CPB plant was established, which paved the way for China's CPB Co. The CPB plant graded unclassified tailings with hydrocyclones. Then, the graded tailings (coarse particles) are dehydrated and concentrated to produce a high-concentration tailing paste that would be mixed with cement to make a fresh CPB using a twin-shaft mixer [21]. In 2006, the Yunnan Huize lead-zinc Mine was the first to use a deep cone thickener for dehydrating and concentrating low-concentration tailing slurry into high-concentration tailing slurry, thus achieving zero tailing emissions [22]. The Wushan Copper molybdenum mine set up China's first paste surface disposal system. However, the temperature at the mine site could drop to −47°C in winter, which made paste transportation difficult. Therefore, heat insulation is applied to paste transportation technology to deal with the impact of low temperatures in winter on pipeline transportation [23]. In 2014, the Xinjiang Jiashi Copper Mine first used a saline-alkali water circulation backfilling system to work in low temperatures and save water usage, thus coping with the severe lack of fresh water in the local area [24]. The CPB plant under construction at the Chalukou mine (Heilongjiang Province) will have a daily backfill capacity of 18000 m^3 and is expected to be China's

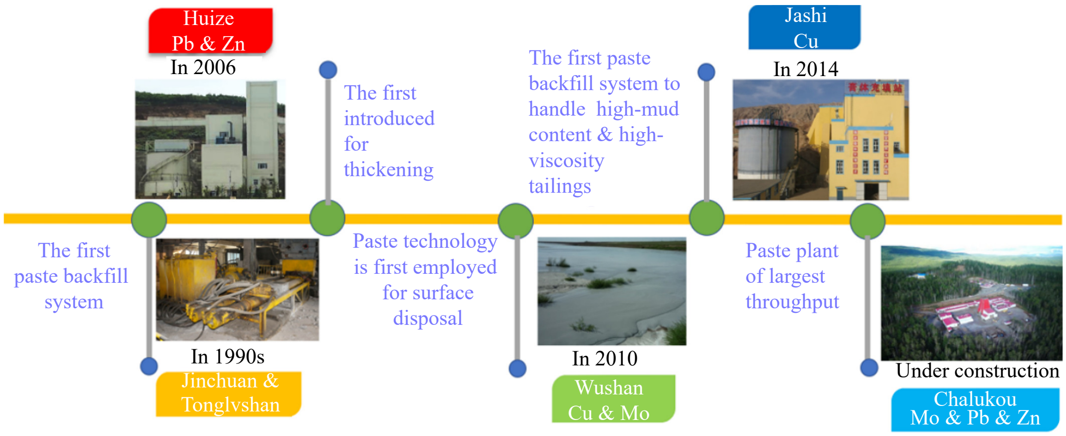


Fig. 2. Development history of CPB in China.

most productive backfill plant [25].

As per the statistics of the Ministry of Natural Resources of China, more than 950 mines were built in 2019, of which 297 mines used paste backfilling. Since 2007, the number of tailing ponds in China has decreased from 14200 in 2007 to 8869 in 2015. Fewer than 8000 tailing ponds exist in China today. Furthermore, the comprehensive utilization rate of tailings increased from 18.9% in 2013 to 27.8% in 2018, and the annual treatment volume increased from 312 million tonnes in 2013 to 1.46 billion tonnes in 2018. No major production safety accidents happen in China for 14 consecutive years since 2008 because of the good safety of backfill mining technology [26–27]. The extensive use of CPB directly reduces the accumulation of tailings and the number of tailing ponds. Moreover, it indirectly decreases the probability of dam failure and protects the ecological environment and people's lives and safety.

3.3. Mixing technology for cemented paste backfill

3.3.1. Brief introduction of CPB mixing technology

CPB mixing is categorized into batch mixing and continuous mixing based on the feeding and discharging methods [28]. Batch mixing involves batch feeding, mixing, and discharging, and then intermittently repeats the process. Continuous mixing is an uninterrupted process that includes continuous feeding, mixing, and conveying [29].

Batch mixing originated in the concrete industry, including self-falling mixers and horizontal mixers [30]. Batch mixers produce well-mixed CPB with a controllable time and an accurate material ratio [31]. However, batch mixers are prone to faults because of their low output and massive equipment. Moreover, measuring the production volume during the intermittent mixing process is difficult because the CPB is a high-concentration fluid. Consequently, the batch mixing process is frequently used to mix loose and dry materials, such as filling materials in coal mines [32].

Continuous mixing primarily includes a mixing drum, a two-stage continuous mixer, and a high-intensity mixer. In addition to simplifying the mixing process, the times of switching-on and switching-off are reduced, and wear rate of the equipment is also reduced. Therefore, the equipment becomes more durable and can better meet industrial development needs. Similar to a production line, continuous mixing considerably improves work efficiency because of its continuous operation, thereby reducing energy consumption.

3.3.2. Problems and challenges of CPB technology

(1) Limited production capacity.

Large-capacity equipment for CPB is important to ensure an annual metal mine production of 10 million tonnes [33]. However, the production capacity of existing CPB mixers is typically <150 m^3/h. The failure to meet mine demand because of the mixer's insufficient capacity considerably limits a paste plant's production capacity.

(2) Inadequate homogenization.

When the raw ingredients (tailings, cement, chemical additives, and water) are mixed, a liquid bridge between particles possibly forms, generating agglomerates [34]. Some of these agglomerates stick to the mixer's bottom and inner walls, rendering them unable to mix and creating an inefficient mixing zone [35]. If they are discharged with the CPB, the transport performance of the CPB will suffer.

(3) Lack of the criterion for mixing homogenization.

Currently, the homogeneity standard for CPB mixing remains similar to that of concrete mixing, although the latter is no longer applicable because of the variability of the paste itself. Some researchers have proposed various criteria after studying the rheological and mechanical properties of the paste. Unifying the standard has a long way to go because of the inadequacies of these standards.

(4) Lack of essential theoretical guidance.

Theoretical research on CPB mixing focuses primarily on the equipment's characteristics, with little attention paid to the fundamental theory of the mixing process [36–37], particularly the characterization of the slurry-to-paste state process during mixing. The idea of a large-volume, intelligent CPB mixing plant is still in the technology accumulation stage because of a lack of basic theory.

4. Research status of CPB mixing technology in China

4.1. Increasing attention to the impact of the mixing process on CPB performance

Previous studies primarily focused on the impacts of raw materials (tailings, cement, water, and additives) and environmental conditions (temperature, pH, pressure, and setting time) on the properties of CPB, with the effects of the mixing process being studied only infrequently (rheology, hydration, and mechanics). The slurry transforms into a paste during this mixing process, thus significantly affecting the production of the microstructure of CPB. For example, cement agglomeration (Fig. 3) will significantly affect the strength of the hardened paste [38]. Therefore, the influence of mixing on the performance of the CPB cannot be overlooked.

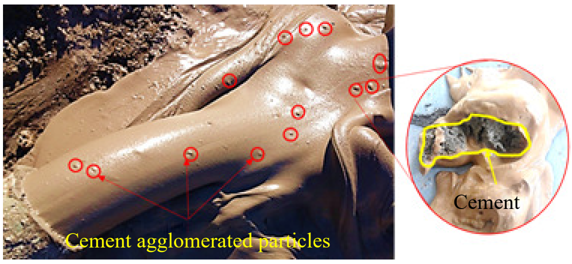


Fig. 3. Cement agglomeration in the unevenly mixed paste.

With the increase in the popularity of CPB, certain academics have become interested in the mixing process. On the basis of rheological theory, some researchers have argued that the paste matrix's inherent structure can greatly influence the rheological properties and the macroscopic flow behavior of CPB [39]. Wallevik [40] believed that the rheological characteristics of CPB prepared under different mixing procedures vary significantly. On the basis of this idea, Han and Ferron [41] and He *et al.* [42] researched the mixing method and speed, discovering patterns that influenced the rheological properties of cement-based materials. Liu *et al.* [43] performed more in-depth research on the thinning and thickening of the CPB under shear during the mixing process, thus establishing the relationship between the rheological properties and particle aggregation. They believed that the changes in the mesostructure determine the rheological parameters of the CPB, referring to the effect of mixing on the rheological properties of the CPB as the "shear history effect".

Some researchers believe that hydration, setting time, and mechanical properties are important properties of CPB related to the formation and morphology of hydration products. Studies [44–46] have demonstrated that a proper mixing time and method can significantly improve the mechanical properties of the paste. Generally, the mechanism of mixing's effect on the mechanical properties of hardened paste is related to changes in early hydration because of the mixing action [47]. However, the current theoretical findings are insufficient to explain the unique rheological phenomenon caused by the paste being mixed and sheared.

4.2. Characterization of the granular-to-paste state process during mixing

CPB preparation, unlike concrete mixing, is a slurry (tailings slurry) and dry powder (cement, chemical additive) mixing process that generally does not require additional water [48]. The formation mechanism for such a granular structure composed of components as diverse as tailings, water, cement, and admixture remains complex [49–51]. Previous research analyzed the mix-composition trends and the impacts of mixer filling levels on the characteristics of mixing microstructure evolution.

Studies have demonstrated that at the beginning of mixing, tailing particles are stained with dry particles and packaged into agglomerates because of mixing between tailings slurry and dry powder [52]. Agglomerate porosity is defined as the voids among agglomerate particles [53]. The droplets in the tailing slurry will continue to bond with the dry powder particles, which may still be present in the slurry under the shearing action of the mixing blades [54]. Through continuous mixing, agglomerates will appear and then expand. Droplets will penetrate pores in the aggregate to form a liquid bridge [55]. When the dry powder particles are thoroughly wetted, the mixture transforms into a hard paste with an uneven surface. As the mixing continues, a portion of the aggregate in the hard paste will break under the shearing action [56], reducing the viscosity of the mixture and forming a suspended soft paste. However, some aggregates remain in the paste and are incompatible with both fresh CPB flow and the generation of sufficient mechanical strength for the hardened CPB. The aggregates in the soft paste will be destroyed during the mixing process, and the mixture will eventually form a liquid-like homogeneous paste.

To facilitate the understanding of the mixing mechanism, a conceptual model of mixture microstructure evolution during mixing was proposed by Cazacliu and Roquet [57], which demonstrated how mixing power evolution shows the various states of the mixture during mixing. As shown in Fig. 4, CPB mixing is divided into five stages. These stages can then be reduced to two processes: dispersion and distribution.

The dispersive process involves the rupture of transient particle aggregates formed by capillary forces in the first moments after water addition. The homogeneity of the mixture is maintained only at the macroscopic level in this process. However, the distribution process is directly related to the homogeneity of the final product [58–59]. It corresponds to the ability of the mixer to spread all the particles within the product. The final result of CPB mixing is macroscopically and microscopically achieving the uniform dispersion of the components of the particles. Mixing can reduce agglomeration, destroy the hydrate film layer [60], improve particle hydration, and change the state of the material from dry powder to either a semi-wet state or a fluid state.

4.3. Monitoring of the CPB mixing evolution

(1) Characterization of the mixing quality.

Mixing aims to achieve paste homogenization, while quantitative homogenization evaluation is a scale for scientifically distinguishing the benefits and limitations of mixing. Few studies on mixing homogenization have been conducted to date. The homogeneous mixing standard for paste is still

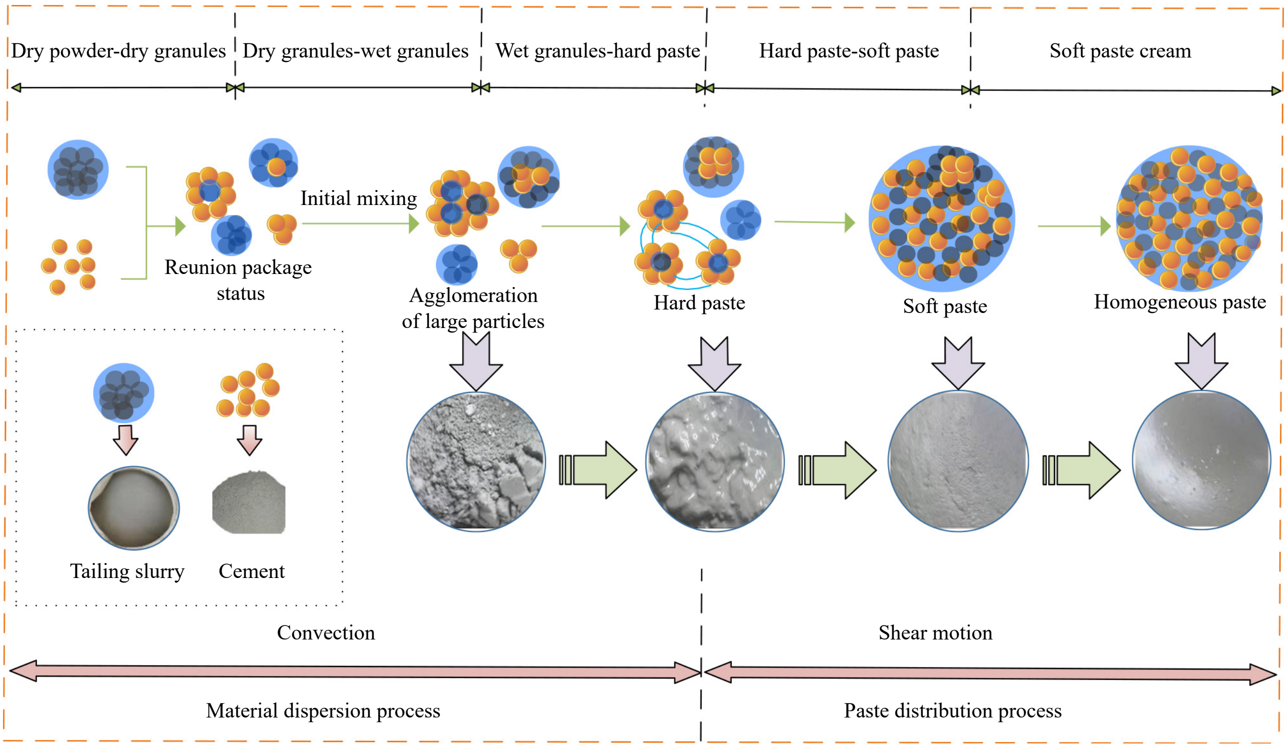


Fig. 4. Main microstructural evolution taking place during CPB mixing and the corresponding mixing stages.

borrowed from the concrete industry [61] (the proportion of coarse aggregates above 5 mm is counted). However, this standard does not work for a paste because the tailings have high fine particle content.

In recent years, researchers have gradually become involved in the field of monitoring mixed homogeneity research. Yan *et al.* [62] evaluated the strength and fluidity of the mixing paste at multiple stages as a criterion for mixing homogenization. Zhou *et al.* [63] referred to the proportion of agglomerates after mixing as the criterion for mixing homogenization. Theoretically, these methods are reasonable, but data collection and feedback are delayed.

(2) Monitoring of CPB homogenization.

Initially, manual sampling was used to verify the quality of paste mixing. Technicians determined the mixing effect by performing tests on samples to obtain the paste performance, such as mechanical properties [64], hydration properties [65], and fluidity [66]. This method exhibits great randomness and serious hysteresis.

With the popularity of industrial automation, intelligent systems such as programmable logic controllers (PLC) [67] and distributed control systems (DCS) [68] have been gradually applied to mining. The start-to-stop operation of equipment, valve switching, and flow monitoring are all controlled by computer programs [69]. Such systems can accurately deliver feed volume and, to some extent, ensure physical homogenization. However, they can only control the mixing time without a feedback loop. Moreover, the systems can neither monitor the mixing quality promptly nor respond to the feedback system, let alone regulate and control the mixing quality accordingly. To compensate for these shortcomings, many scholars have proposed smart optimization schemes, such as neural network control [70], fuzzy control [71], and integrated intelligent control [72–73]. However, no practical results have been achieved because they are still in the early stages.

4.4. Research on special equipment for CPB mixing

The mixing equipment can be classified as a self-falling mixer [74] and a forced mixer [75] based on the mixing mechanism. The common mixing equipment is shown in Table 1.

Forced mixers are commonly used because of the high concentration and fluidity of the paste, and self-falling mixers are currently the best choice for mixing low-fluidity concrete, such as in water conservation projects [76]. The two-stage and activating mixing processes are used more among forced mixers. The two-stage continuous mixer employs a twin-shaft mixer plus a spiral mixer, which has both mixing and storage functions. The activating mixing technology is matched with the twin-shaft mixer, which eliminates cement particle agglomerates better.

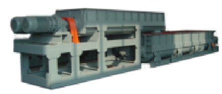
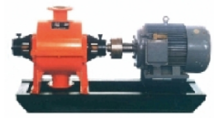
5. Cases of CPB mixing technology in China

This review uses engineering cases to analyze the four commonly used slurry mixing methods at present and discusses their respective applicable situations and functional characteristics.

5.1. Two-stage continuous mixing

Fig. 5 shows the paste backfilling plant built in 2011 in a lead-zinc mine in Guizhou, China. The preparation and conveying capacity of the single plant is 50–100 m^3/h (Table 2),

Table 1. Performance table of special mixing equipment

Name	Advantages	Type	Disadvantages	Capacity / ($m^3 \cdot h^{-1}$)	Energy consumption	Picture
Self-falling mixer	Simple structure, stable operation, low noise, and low energy consumption	Batch	Low mixing quality and poor production efficiency	20–60	High	
Horizontal batch mixer	Good mixing quality and high production efficiency; suitable for coarse-grained tailings	Batch	Low processing capacity, prone to wear equipment, and inefficient area	40–100	Rather low	
Twin-shaft continuous mixer	Simple structure, high durability, and ability to meet requirements for continuous operation	Continuous	Insufficient preparation capacity	60–120	Rather high	
High-intensity mixer	Eliminating cement agglomeration; offering homogenized mixing and better fluidity	Continuous	Low production capacity	50–100	High	
Forced drum mixer	Suitable for mixing low-concentration and fine-grained materials	Continuous	Limited mixing concentration	30–160	Rather low	

its maximum backfill volume at a time is 1200–1500 m^3, and it adopts a two-stage continuous mixer.

Concentrated tailings, fine sand, cement, and water are fed into the twin-shaft blade mixer in the proportions specified by supply lines. Each material is initially mixed in the mixer to form a suspended state and then sent to the double-spiral mixing conveyor for mixing, storing, and delivering. A fluid, plastic paste form of the slurry is produced after being continuously mixed in two stages. Then, it is transported into the pipeline from the discharge port and pumped through boreholes or transported to goaf by gravity.

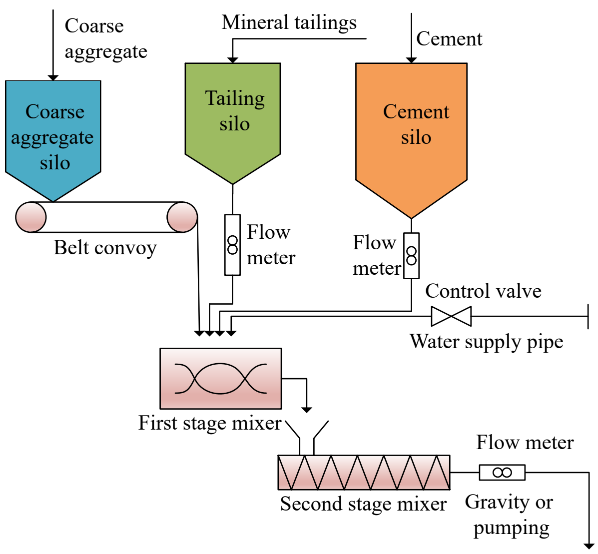


Fig. 5. Schematic of backfilling and mixing system for a lead-zinc mine in Guizhou.

The two-stage continuous mixer is the most common type of mine backfilling and mixing equipment. It has good compatibility with supporting equipment such as deep cone thickeners and piston pumps. Slurry mixing occurs primarily in the double-shaft mixer, where the materials are forced to mix quickly before being transferred to the spiral conveyor for mixing and transportation [77]. The two-stage mixer has a simple structure and is suitable for mixing materials that contain coarse aggregates. It has high efficiency and good mixing quality, thus allowing for macroscopic paste homogeneity [78].

5.2. High-intensity mixing

CPB is transported by gravity in an iron ore mine in Wuhan, China (Fig. 6). A combination of a blade mixer and a high-intensity mixer is used in the mixing process. First, the high-concentration tailings are piped from the tailings pond

Table 2. Basic parameters of two-stage continuous mixers

Mixer name	Trough size	Production capacity / ($m^3 \cdot h^{-1}$)	Blade diameter / mm	Rotation speed / ($r \cdot min^{-1}$)	Motor power / kW
Double-shaft blade mixer	4780 mm × 1236 mm × 850 mm	50–100	700	30–80	45
Double spiral mixing conveyor	6840 mm × 1650 mm × 1120 mm	50–160	800	20–50	2 × 35

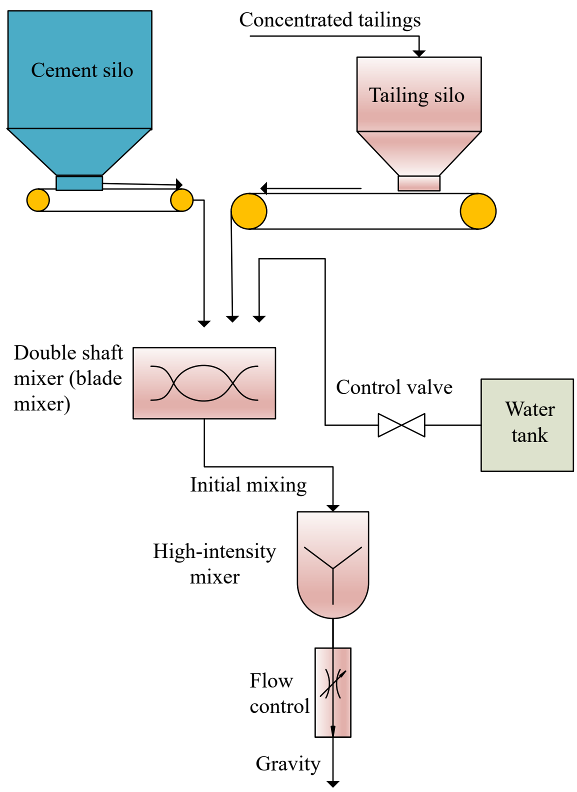


Fig. 6. Schematic of the backfilling and mixing system for an iron ore mine in Wuhan.

to the double-shaft mixer, which receives aggregate, water, and cementitious materials from each supply line. Second, the slurry is powerfully mixed by the double-shaft mixer to enable the viscous high-concentration slurry to achieve physical macroscopic homogeneity. However, because of the high viscosity of the slurry itself, it still contains many flocculent aggregates. Therefore, the slurry is sent to a high-intensity mixer. After vigorous high stirring at high speed, the flocculant is considerably reduced. The prepared paste satisfies the backfilling requirements and directly flows to the underground goaf via the pipeline.

The high-intensity mixer can break the structure of hydration products on the surface of particles by forced force and high-speed movement [79] and forcibly disperse the agglomerated particles in the mixture. This approach enables the cement particles to be completely distributed, thereby ensuring paste homogenization and overcoming the inhomogeneity of the traditional mixer, which can considerably reduce the consumption of cement. However, because of the quick rotation speed of the high-intensity mixer, the mixer blades will be severely worn. Thus, high-intensity mixing technology is not suitable for CPB that contains coarse aggregate. Moreover, high-speed mixing consumes a large amount of energy and has, therefore, not been widely used in mines.

5.3. Batch mixing

Fig. 7 shows the CPB mixing system of a lead-zinc mine in Guangdong, China. It adopts a batch mixing process and uses multiple batch mixers simultaneously. One example is given for illustration.

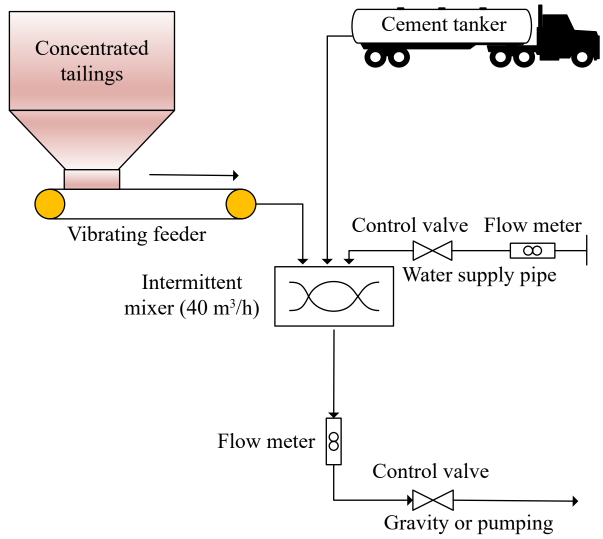


Fig. 7. Schematic of the CPB system for a lead-zinc mine in Guangdong.

First, concentrated tailings are discharged from the storage bin and transported to the horizontal batch mixer through the vibrating feeder. The cement is transported by the cement tanker and mixed with the tailings into the mixer through the chute. Under the forced force of the blades, the paste circulates the mixing shaft, and the particles collide and rub against each other until they are homogeneous. When pumped, the paste flows to the goaf through the pipeline.

Batch mixing requires accurate measurement of the mixed materials before mixing preparation and precise control of the mixing time. Thus, the paste prepared by the batch mixer has excellent homogenization. Batch mixing is inefficient, which is why multiple sets of equipment are generally used to work simultaneously, thereby greatly reducing the reliability of the system and increasing energy consumption. Moreover, the feeding equipment frequently starts and stops, so it is worn heavily. Batch mixing must ensure that raw materials are in a fresh state to prevent hardening; otherwise, it will cause a production stoppage. Therefore, the batch mixing process is mainly used for mixing loose raw materials, such as coal mines, which are rarely used in metal mines.

5.4. Drum mixing

A nickel mine in Gansu Province uses unclassified tailings, coarse aggregate, and cement to prepare CPB (Fig. 8). The coarse aggregate used in the mine is derived from open-pit cobblestone, whose size is too large to meet the requirements of pipeline transportation. Therefore, cobblestone with a particle size greater than 20 mm needs to be first screened out with the help of machinery. The wet rod mill [80] and classifier are used for dehydration and mud-removal until they are processed into 0–5 mm rod-milled sand as the raw material.

The mine adopts the drum (ϕ = 2 m) mixing process. The drum's small volume cannot meet the requirements of large-volume CPB mixing. To improve efficiency, mine companies designed a powerful mixing drum (120–150 m^3/h) by increasing the number of blades to improve the motor power.

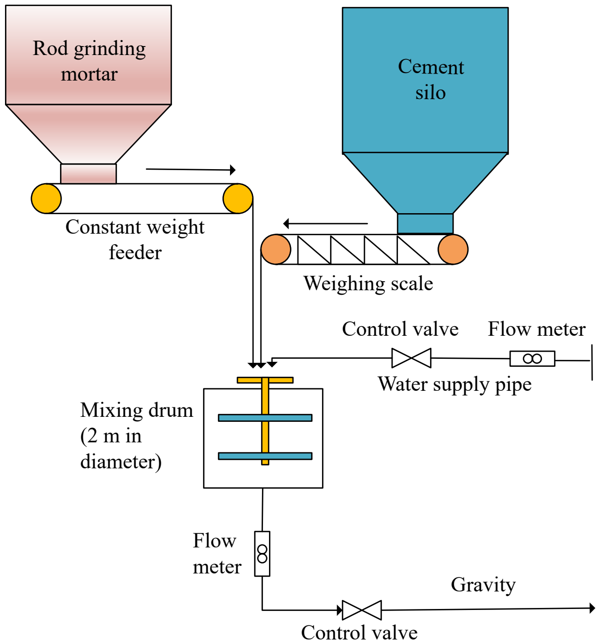


Fig. 8. Schematic of the CPB system of a nickel mine in Gansu Province.

The mortar and cement are stored in the mortar silo, weighed by a weighing scale, and then transported to the mixing drum for mixing. After that, the paste flows from the discharge port through the pipeline to the goaf.

Drum mixing is the most used process in the water-sand filling plants and is the standard equipment for preparing low-concentration backfilling paste. It mainly relies on the force of the blades to make the particles collide and rub against each other and eventually become homogeneous. However, it is seldom used in CPB technology because of the vortex phenomenon in the mixing drum. Drum mixing is widely used in many mines in China because of its reliability and stability despite its high energy consumption.

6. Development trend of CPB mixing technology in China

6.1. Challenge

The CPB mixing technology development is confronted with many obstacles, such as the lack of large-capacity and fine mixing equipment, insufficient research on the effects of additives and fiber materials on mixing, and a shortage of reasonable and unified mixing monitoring schemes of the mixing process. In addition, relevant research and development on low-consumption mixing equipment are insufficient.

6.1.1. Large-capacity CPB mixing system

Metal mine capacity is gradually increasing, surpassing 10 million tonnes [81], necessitating the development of large-capacity mining equipment to match large mine production capacity. Currently, the production capacity of a single mixing plant ranges from 60 to 120 m^3/h, with a maximum capacity of 150 m^3/h [82]. Compared with other CPB system equipment, the overall capacity of the mixers is suffering, thus limiting the capacity of the CPB system. If the number of equipment is simply increased to meet the demands, a large amount of construction land will be occupied, and the construction cost will rise accordingly. Therefore, the development of large-capacity mixing equipment is the key to resolving the CPB capacity shortage.

Some scholars argue that the existing equipment can be scaled up reasonably. Yang *et al.* [83] has increased the capacity of small equipment from 60–100 m^3/h to 150–180 m^3/h by modifying the capacity of the mixing equipment and increasing the size of the mixing blades. However, due to the complexity of the flow field distribution in the mixing tank, large particles of the material are deposited, and the mixing quality is not ideal. This research method provides new insights into the development of large-capacity mixing equipment. However, these works are still in the initial stage, and engineering applications are still confronted with great difficulties.

6.1.2. Admixtures and reinforcement of the paste materials

Admixtures are usually added during mixing to improve the quality of the CPB, but they will affect the mixing process of the paste in some way. On the one hand, the addition of admixtures facilitates mixing. For example, the water-reducing agent [84] reduces the particle interaction force [85], which aids in the homogenization of cement and tailings particles, thus shortening the mixing time [86–87] and improving mixing efficiency [88]. However, some admixtures, such as early strength agents [89], which can accelerate the hydration reaction and thereby increase the force between particles [90], are not conducive to the homogenization of CPB (Fig. 9).

In addition, fiber materials such as steel fibers [91] and alkali-resistant glass fibers [92] can be added to increase the mechanical properties of the CPB [93]. Some scholars have

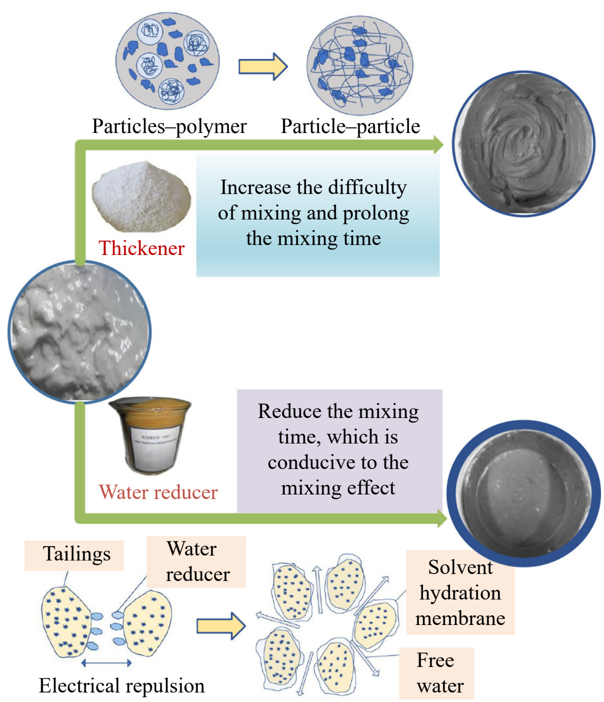


Fig. 9. Comparison of the effects of thickeners and water reducers.

even added rubber to cement-based materials [94], which not only strengthens their ductility but also provides a convenient way to dispose of waste tires. However, these fiber materials hinder the mixing process. The steel fiber, in particular, will wear out the mixer. Unfortunately, these issues have received insufficient attention.

Adding additives and fiber materials to cementitious materials is a common way to improve their performance. However, the mixing process of combining them, however, has received little attention. When adding fibers and additives, some researchers believe it is important to consider not only the compatibility of the materials but also the mixing methods used based on the properties of the materials. For example, when the steel fiber material is processed, vibratory mixing can ensure that the steel fibers are evenly distributed throughout the paste [95–96].

6.1.3. Monitoring method and technology for CPB homogenization

The application problem of online homogeneity monitoring during CPB mixing has yet to be effectively solved. Scholars have proposed a variety of monitoring methods, the majority of which employ sampling to assess uniaxial compressive strength [97] and fluidity [98] (slump or rheological parameters). The procedure entails sampling different batches of mixed CPB, then testing slump, rheological parameters, and mechanical parameters to analyze the differences between batches of samples to better understand CPB homogeneity during mixing. This method, however, has a significant lag and cannot adjust the mixing parameters in real time.

Slurry homogeneity is related to rheological parameters, according to some studies. If the rheological characteristics of the mixture can be obtained in real-time, the homogenization of the paste during mixing can be better understood. The rheological characteristics of the mixture are directly related to the power or torque of the mixer. Therefore, monitoring motor torque or power changes can be used to understand CPB homogeneity [99]. For example, a torque sensor is mounted on the mixer shaft to measure torque changes during the mixing process. However, the factors that affect the power consumption have large fluctuations [100], and it is difficult to feedback on the subtle changes of the CPB, and the accuracy is insufficient; therefore, online monitoring of homogenization during mixing is still a nodus.

6.1.4. Lower energy consumption

With the promotion of the carbon peak in China [101], reducing energy consumption has become the goal pursued by all walks of life. For CPB technology, future development must be aimed at lower energy consumption. From the comparison of CPB's existing system and CPB's future development trend (Fig. 10), the deep cone thickener can be transformed into a non-powered structure [102]. For example, the rake-less deep cone thickener could almost achieve "zero energy consumption". In addition, paste transport tends to be gravity transport [103], eliminating the energy consumption of piston pumps and other supporting equipment. Therefore, the mixing process still consumes a lot of energy, which violates China's "carbon neutrality" development model.

To reduce the energy consumption of the CPB mixing, the first step is to reduce the ineffective operation time of the mixer, and secondly, to optimize the equipment structure, such as rationally arranging the number of blades [104]. To significantly cut energy consumption, developing new low-carbon mixing equipment is a fundamental method, and the equipment should be based on particle size and production requirements. Gravitational potential energy, for example, can be used to mix tailings, cement, and admixtures between the CPB plant and the goaf. The energy consumption of CPB

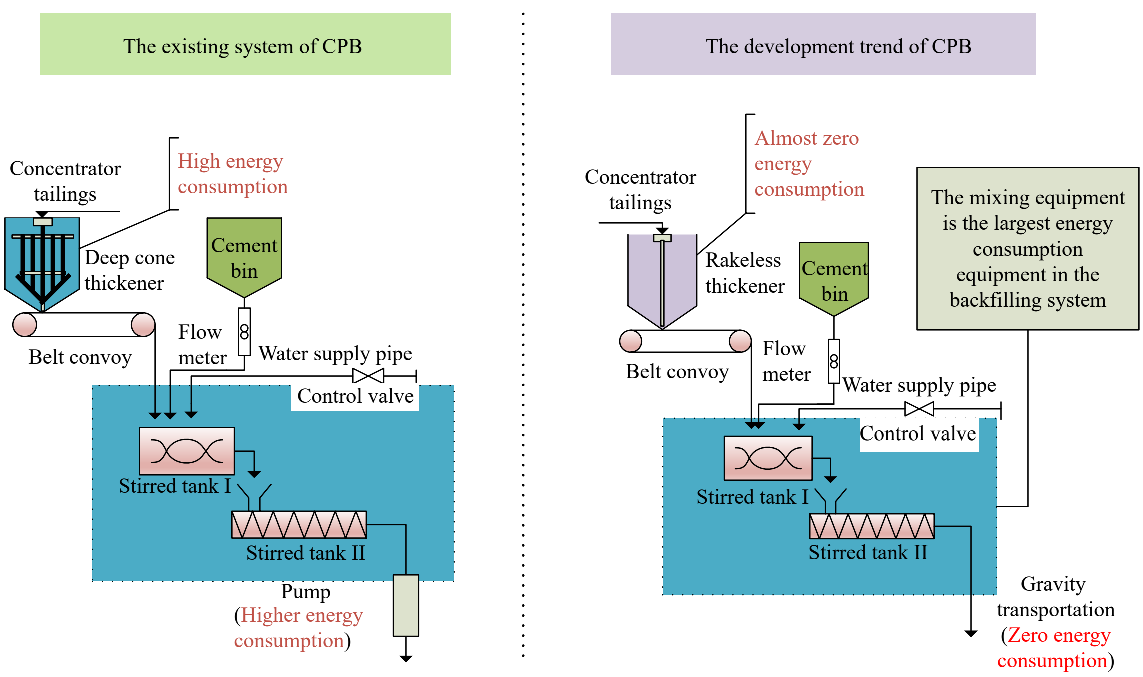


Fig. 10. Comparison of the traditional paste backfilling process and the development trend.

mixing can thus be reduced to zero. Although the technology is still in its infancy, it provides a fresh perspective on future development.

6.2. Prospects

CPB technology will face more challenges in the future as mining depth increases. Furthermore, the use of artificial intelligence in CPB technology cannot be overlooked.

6.2.1. Intelligent control of the operation system

A comprehensive control solution includes precise mixing speed, pump delivery flow, and admixture amount control, among other things [105]. It is realized by intelligent control, which enables automatic control of factors such as feed volume and additive content [106], and the accurate perception of the CPB performance varies as operating parameters change.

In most cases, the control system can only adjust the amount of feed-in and out, and it has issues with low intelligence and poor adaptive ability. Therefore, developing an intelligent mixing control system is critical. Qi *et al.* [107] has carried out a lot of research in this field, proposing to improve the control system through artificial intelligence. During this process, problems in each link of the CPB are subdivided into several links and data through sensors are collected, and all of these are processed intelligently. Many sensors are applied to collect and relay various parameters from the production process to the control center. Finally, the intelligent control system directs the operation of the machines. The benefits include significant labor savings and the ability to run factories 24 h a day while reducing human error.

6.2.2. Simplification of the mixing operations

(1) Research and develop a new type of mixer.

To meet the needs of various types of CPB plants, some new mixing mixers were developed, and they have greatly improved mixing efficiency. For example, the twin-shaft horizontal mixer is ineffective at homogenizing extremely fine tailings, but the problem could be solved by using a multi-shaft mixer with low energy consumption and high efficiency. A new overflow blade mixer was developed specifically for CPB technology [108]. It can control the mixing time, ensure the mixing quality and allow for continuous preparation. However, it consumes a lot of energy and is currently only used in a few mines.

(2) Optimize mixer performance and simplify the mixer operation.

Optimizing and transforming existing equipment can increase production capacity. To reduce on-site mixing time and increase the moving distance, Yang *et al.* [47] designed a truck-mounted paste mixer combined with a concrete mixer truck. This article believes that the two-stage mixer can be simplified into an integrated device to perform all mixing, storage, and transportation functions. This reduces the space occupied by the equipment, increases production capacity, promotes cooperation among workers, and enhances productivity.

6.2.3. Machine learning for paste parameters

Machine learning is the core technology of big data processing and artificial intelligence [109]. The internal laws of data are investigated using independent retrieval of large amounts of data. Machine learning can be used to convert some key parameters in CPB, such as mixing power, water volume ratio, and transportation pipeline, into numerical models [110].

To model the mixer parameters, first determine the main parameters, secondary parameters, and constant parameters; then designate one of the main parameters as the driving parameter and establish a link between it and other parameters using a reasonable expression; and finally, write the parameterized program and create a running model. In the actual application of CPB, relevant parameters must be corrected and calibrated to eliminate errors caused by external factors. Significant time, labor, and financial costs can be saved in the future by using parameterized intelligent programming instead of extensive experiments [111].

6.2.4. Application of numerical simulation to mixer development

Numerical simulation is the process of evaluating parameters such as spatial geometric and engineering information of objects using computer graphics, databases, and other technologies [112]. The particle movement path of CPB in the mixing process is a complicated problem that is difficult to comprehend through physical experiments. To better understand the movement form of particles in the mixer tank, numerical simulation can be combined with limited experiments.

Numerical simulation methods have long been applied in the field of CPB. The Taiping Coal Mine in Shandong Province used FLAC^{3D} to establish numerical simulations to analyze slope stability, roof movement, and deformation [113]. Nowadays, computational fluid dynamics (CFD) and discrete element method models (DEM) have also been widely used in the field of CPB mixing. CFD can simulate and analyze how the flow field changes with the passing of mixing time and how different parameters affect the mixing process. Kozić *et al.* [114] used CFD to analyze the stress of twin-shaft mixing under non-Newtonian fluid. CPB can be regarded to be composed of particles, so DEM is also widely used in CPB mixing technology research. DEM mainly simulates the movement path of particles during mixing and analyses the degree of mixing. Gao *et al.* [115] studied the relationship between the rheological properties of CPB and the degree of mixing in the mixing process by DEM. With the advent of supercomputers, numerical simulation enables us to better understand mixing.

6.2.5. Underground mobile mixing station

Deep mining is a trend for the future development of mines [116]. China's mining depth may even exceed 1000 m [117]. The ground temperature gradually rises with the increase in depth, and the increase in ground pressure may even cause rock bursts [118]. Additionally, excessively deep wells increase mining costs.

To address the challenges of deep underground solid mineral resource mining [119–120], the ground-breaking theoretical and technical conceptualization of fluidized mining has become a research hotspot in recent years. The novel idea refers to the *in situ* conversion of deep underground solid mineral resources into gas/liquid/solid states to achieve unmanned intelligent underground mining-sorting-backfilling. A new mining model will be used to replace traditional resource excavation, transportation, and utilization modes. To make this a reality, equipment that can move underground must be built. The most important thing for underground mixing equipment is to miniaturize it [121] so that it can be equipped with a mobile system and meet the requirements of free installation and disassembly in underground space.

7. Conclusions

With public awareness of environmental protection increasing, the future of mining production will inevitably pursue low-carbon and efficient development. CPB technology will be an effective way to carry out environmental management in the mining industry and a major solution to the pollution of mining. However, there is still a long way to go to achieve intelligent, efficient, and inexpensive CPB mixing systems. To this end, the article systematically reviews the application of mixing systems in CPB and focuses on the current situation.

(1) CPB mixing means dispersing CPB components into a mixed volume and then turning a wet granular mixture into a granular suspension microstructure. The promotion effect of mixing on CPB performance has not been fully explored due to the lack of research for a long time. Therefore, more advanced and efficient mixing technologies are developed to cut down the amount of cement and reduce energy consumption, making the CPB technology more environmental-friendly.

(2) The CPB mixing technology has progressed significantly in recent decades. New mixing equipment has indirectly promoted the development of CPB mixing, but a large-capacity mixer remains a critical issue for CPB mixing that must be addressed urgently.

(3) Machine learning and numerical simulation are conventional methods for studying mixing technology and developing mixing equipment. Model analysis of mixing equipment parameters and raw material parameters can provide an intuitive understanding of the flow field inside the tank, thereby obtaining the microstructure change of the mixture, perfecting the basic mixing theory, and optimizing the mixing technology.

(4) Mixing technology and equipment should be developed to reduce energy consumption to comply with China's low-carbon policies. A challenging frontier of green technology is the fluidized mining of deep underground solid mineral resources. This novel concept will pave the way for improving fluidized mining technology, allowing for the safe, efficient, and environmentally friendly extraction of deep underground solid minerals. The development of intelligent underground mining-sorting-backfilling equipment that can move underground is at the core of this technology.

(5) Standards are the driving forces behind technological progress. However, CPB homogenization research is limited to conceptual and numerical simulation levels. A set of objective criteria for mixing process adjustments have become increasingly important owing primarily to the increased demand for CPB.

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Conflict of Interest

Shenghua Yin is an editorial board member for this journal and was not involved in the editorial review or the decision to publish this article. The authors declare that they do not have any competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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