Key theory and technology of cemented paste backfill for green mining of metal mines

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A B S T R A C T

To reduce or eliminate environmental damage during mining processes, green mining practices have emerged as a focal point in China's metal mining research. Cemented paste backfill technology plays a pivotal role in promoting green mining within the metal industry. The technology allows safely backfilling of surface tailings into underground mining airspaces, effectively addressing the challenges associated with tailings storage and underground goaves. In this paper, we introduce the paste rheology theory system, which forms the theoretical backbone of cemented paste backfill. We delve into key technologies such as paste thickening, mixing, transportation, and the use of economical, low-carbon materials. Additionally, we analyze macro and micro-mechanical properties, *in-situ* performance monitoring, barricade construction, intelligent control, and numerical simulations of the process. We establish several demonstration projects, both domestic and international, that utilize cemented paste backfill technology to foster greener mining practices. Cemented paste backfill technology is widely used all over the world. It has evolved from its initial stages to being recognized as an advanced application by various ministries and commissions. Ultimately, we propose future research directions for cemented paste backfill technology in the context of eco-friendly metal mining. These perspectives encompass theory, technology, equipment, and mode, which can strongly contribute to the sustainability of the mining industry in China.

1. Introduction

Metal mineral resources hold a strategic position in China's modernization, being pivotal to both national security and economic lifelines [1]. However, the mining process for these metal mines generates a large amount of tailings. These are often stockpiled in surface tailings ponds, causing environmental damage and the risk of dam breaches. Moreover, the process leaves behind numerous underground goaves, posing a severe threat to mining safety. Consequently, both the underground goaves and surface tailings ponds have become major sources of danger and pollution in metal mines [2]. Since the 18th National Congress of the Communist Party of China, the state prioritized the construction of an ecological civilization as a fundamental plan for sustainable development. The report of the 20th National Congress of the Communist Party of China emphasized the need to develop green and low-carbon industries, advocate for green consumption, and promote the formation of green and low-carbon production and lifestyles. To reduce or eliminate environmental damage during mining processes and to embody the principle that "lucid waters and lush mountains are invaluable assets," green mining practices have emerged as a focal point in China's metal mining research [3–5].

Widely used in tailings disposal and goaf treatment, full tailings paste filling technology is renowned for its safety, environmental protection, economic soundness, and high efficiency [6,7]. This technology can curb the hazards of goaf and tailings ponds at the source. It embodies the principle of "one waste cures two hazards" and maximizes the resource utilization of tailings as solid waste [8]. As such, it has become an important technical support for large-scale, green, and efficient mining of mineral resources, playing a key role in promoting green, low-carbon development of mines and ensuring resource security. Introduced to China nearly 20 years ago, paste filling technology has rapidly developed and is recognized as an advanced, applicable, and demonstration technology by many national ministries and

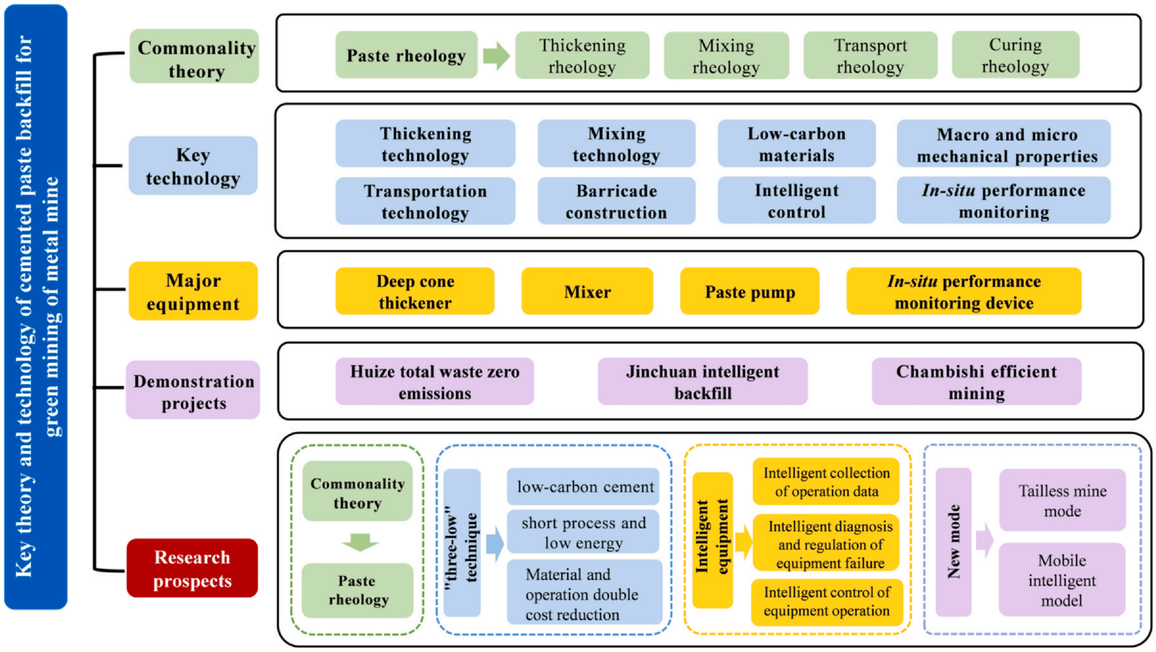

Fig. 1. Overall diagram of green mining illustrating the key theory and technology of cemented paste backfill for green metal mining.

commissions. In December 2017, the Ministry of Environmental Protection of the People's Republic of China included the "Mine goaf tailings cemented paste backfill technology" in the "2017 National Advanced Pollution Prevention and Control Technology Catalogue (Solid Waste Treatment and Disposal Field)" as a demonstration technology. Further endorsing this technology, the Ministry of Natural Resources of the People's Republic of China, in August 2022, included full tailings paste filling technology as an efficient mining technology in its "Catalogue of Advanced Applicable Technologies for the Conservation and Comprehensive Utilization of Mineral Resources (2022 Edition)." Given the national policy orientation and the technical advantages of this method, its application has seen a significant rise across China [9–11].

This paper provides a comprehensive summary of the key theories and technologies of cemented paste backfill in China (Fig. 1). Building on the commonality theory of paste rheology, we proposed a theoretical system that includes full tailings thickening rheology, mixing rheology, transport rheology, and curing rheology. We have systematically researched key technologies such as paste thickening technology, mixing technology, transportation technology, economical and low-carbon materials, macro and micromechanical properties, *in-situ* performance monitoring, filling barricade construction, and intelligent management and control. We have also established several demonstration projects based on cemented paste backfill technology for green mining both domestically and internationally, including the Huize lead–zinc mine in Yunnan, the Jinchuan Nickel Mine in Gansu, and the Chambishi Copper Mine in Zambia. Finally, we proposed future innovative research directions for the green mining of metal mine cemented paste backfill. These suggestions span across various aspects such as theory, technology, equipment, and mode, which can strongly support the high-quality development of green mining practices in China.

2. Paste rheology theory

2.1. Rheology of full tailings in thickening

Thickening of full tailings exhibits a wide range of concentration variation (from 30wt% to 70wt%), significant changes in the floc structure (from particle to floc to floc network), and prominent rheological behavior under mud layer pressure. Traditional rheological parameters, such as shear yield stress and plastic viscosity, fall short in describing the rheological behavior of the full-tailings slurry throughput throughout the entire deep thickening process. To address this, a rheological characterization system was developed for the full-tailings thickening process. This system employs three parameters: gel point, compressive yield stress, and the hindered settling function [12–14]. As the thickening process progresses, the concentration reaches a critical value where the flocs within the bed interconnect, forming a network structure with the strength to resist external forces. This critical value is referred to as the gel point [15]. Compressive yield stress refers to the stress required to further increase the slurry concentration when the slurry network structure yields and compresses at a certain concentration [16]. The hindered settling function is a combination of the hindered settling factor, Stokes drag coefficient, and particle volume [12]. Essentially, the hindered settling function represents the slurry viscosity per unit area or the surface density of the viscosity, which is inversely related to permeability and free settling velocity.

The traditional settlement thickening model has been mainly based on the C–C theory (Coe–Clevenger theory) [17] and B–W theory (Buscall–White theory) [18]. While the C–C theory applies only to the free settling zone and does not consider the interaction between flocs, the B–W theory considers the floc network structure but only applies to the compression settling zone. Therefore, a continuous steady-state thickening model under shear action was established. This model combines the C–C and B–W theories, using the gel point as the dividing line. This model is depicted in Fig. 2.

2.2. Rheology of paste mixing

The mathematical description of the evolution process in the microstructure of the full-tailings paste during mixing is based on the relative structure coefficient λ' [19]. During the mixing process, particles within the paste system are continuously dispersed and overlapped owing to the action of the particle surface. This results in two processes: the destruction of the mesostructure and the reconstruction of the structure. Under shear action, the structural destroy rate surpasses the reconstruction rate, causing the relative structure coefficient λ' to decrease. However, as the mixing disperses the particles further, the probability of mutual contact increases, thereby enhancing the

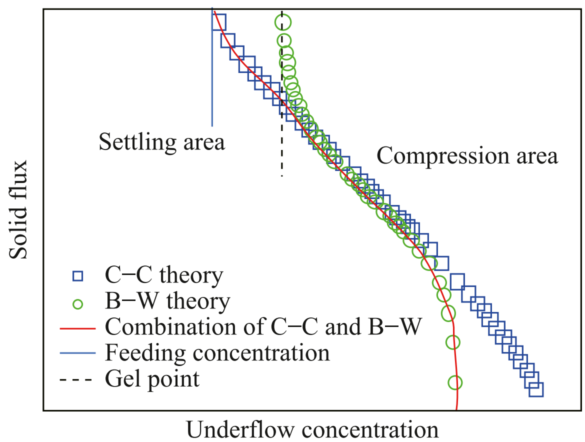

Fig. 2. Combination of the C–C theory and B–W theory. Reproduced with permission from Ref. [19].

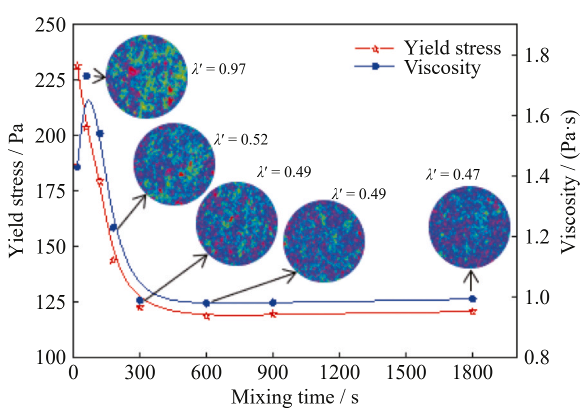

Fig. 3. Evolution of rheological properties and λ' with mixing time (modified from [20]). Reproduced with permission from Ref. [19].

reconstruction rate. Eventually, a dynamic balance between destruction and recovery is achieved. Therefore, as the mixing continues, the relative structure coefficient λ' of the paste gradually decreases until it reaches a stable state [20], as shown in Fig. 3.

The rheological parameters of the paste are consistent with the changing trend of the relative structure coefficient. The shear induced by mixing breaks down the microstructure of the paste, resulting in a decrease in the structure coefficient and yield stress. This, in turn, improves the fluidity of the paste [20]. Notably, viscosity exhibits an upward trend at the beginning of mixing. This occurs because as the material soaks, its viscosity rises rapidly, peaking before it starts to decrease under the action of shear.

The chemical composition of full-tailings has a significant influence on the paste rheology [19]. Physical Mixing is a practical way to reduce yield stress and viscosity. Moreover, chemical materials added during the mixing, such as superplasticizer, can also improve the rheological properties of paste [21–24].

In addition to changing the rheological properties of the paste through physical mixing, some additives are usually added during the mixing process to reduce yield stress and viscosity, such as ordinary water reducing agent, superplasticizers, *etc.*

2.3. Rheology of paste in pipeline transportation

In the complex filling pipe network, accurate prediction and regulation of pipeline resistance are crucial when transporting paste. The traditional slurry resistance calculation method often falls short in resistance prediction, leading to pipeline plugging and explosion.

The high concentration of paste, coupled with the irregular shape of tailings particles, results in a thin, low-viscosity slip layer forming at the pipeline wall during fluid flow. This creates a wall slip phenomenon between the fluid and the wall, also known as the pipeline wall slip effect [25]. The relative motion between the paste and the contacted wall during pipeline transportation leads to a stratified laminar flow within the pipeline. Accurate calculation of pipeline flow resistance can only be achieved by considering both the rheological properties of the paste and the wall slip effect.

In recent years, the depletion of shallow resources has made deep mining an inevitable trend in metal mining. However, deep mining affects filling in two significant ways: high well depth prolongs pipeline transportation time, and temperature increases with depth. Therefore, along with pipeline wall slip, the influence of time and temperature on pipeline resistance should also be considered. Studies have found that as temperature increases, the yield stress and viscosity of the paste gradually decrease [26].

Considering the wall slip effect and the time–temperature effect of rheology [19], a paste pipeline transportation resistance model was established based on the Buckingham equation.

$$\begin{cases} i(t,\,T) = \frac{16}{3(8\beta_c\eta_B + D)}\tau_{y0}\exp\{-k[t + c_1(T-30)]\} \\ \quad + \frac{32v}{(8\beta_c\eta_B + D)D}\{\eta_{B0} - m[t + c_2(T-30)]\}, & t \le t_{total} \\ i(t,\,T) = i(t_{\text{total}},\,T), & t > t_{total} \end{cases} \tag{1}$$

where i is the pipeline transportation resistance, t is the time, T is the temperature, β_c is the slip coefficient, D is the pipeline diameter, v is the flow velocity, τ_{y0} is the yield stress, η_{B0} is the plastic viscosity, k and m are the thixotropic time parameters, c_1 and c_2 are the fitting coefficients.

2.4. Rheology of filling body

Presently, research on the rheology of the filling body, both domestically and internationally, mainly concentrates on the creep of the filling body. However, studies on stress relaxation, long-term strength, elastic aftereffect [27,28], and flow [29] of the filling body are relatively scarce.

Given its numerous pores and low strength, the filling body is prone to early damage under stress. Therefore, it is essential to consider this damage when formulating the creep constitutive equation for the filling body. By introducing a damage variable into the Burgers model [30], we can derive an improved constitutive equation for the filling body [31]:

$$\varepsilon(t) = \frac{\sigma_0}{1 - D(\sigma,\,t)}\left[\frac{1}{E_M} + \frac{1}{\eta_M}t + \frac{1}{E_K}\left(1 - e^{-\frac{E_K}{\eta_K}t}\right)\right] \tag{2}$$

where ε is creep stain, $D(\sigma,\,t)$ is the damage variable at loading time t, σ_0 is the stress level, E_M and E_K are the deformation moduli, η_M and η_K are the viscosity coefficients.

The improved creep damage constitutive equation comprehensively considers the influence of loading time and stress level on creep parameters, reflecting the weakening of parameters over time and the damage degradation law of materials.

3. Key technology of cemented paste backfill

3.1. Economic low-carbon paste material

Paste backfill materials are generally composed of inert materials, cementitious materials, and modifiers. The primary component of the paste, the inert material, typically comprises full tailings and serves as the skeleton support. Cementitious materials mainly serve to bind, enabling the inert materials to coalesce into a solid entity with a certain degree of strength. Modifiers play a critical role in enhancing the

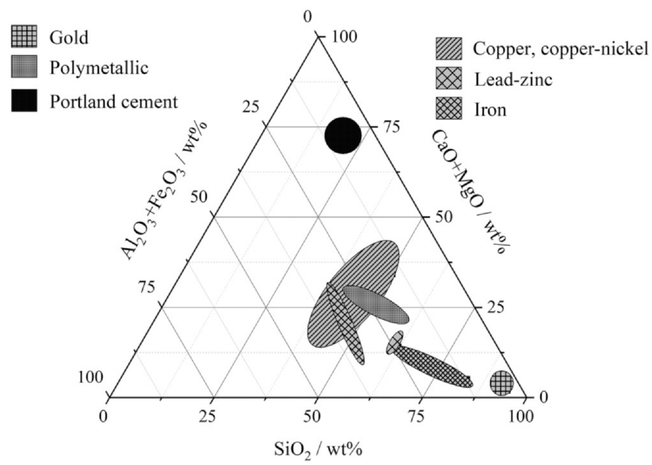

Fig. 4. Distribution characteristics of ternary phase diagrams of different types of metal tailings.

fluidity, initial and final setting, and strength of the paste [32]. Paste filling reflects the characteristics of the new green, low-carbon, economical, and environmentally friendly era, with an emphasis on energy conservation and emission reduction. These attributes are evident right from material selection, thereby fostering the achievement of the "double carbon" goal.

3.1.1. Inert material

(1) Composition properties. In 2021, China produced an estimated total of 1.42 billion tons of tailings. Iron tailings accounted for 610 million tons (43.04%), copper tailings made up 390 million tons (27.63%), and gold tailings comprised 160 million tons (11.33%). The remaining 130 million tons were from other nonferrous metals, and approximately 120 million tons were non-metallic tailings [33]. These tailings primarily consist of silicon, aluminum, calcium, magnesium, iron, and other oxides. The main mineral components are quartz, feldspar, and mica. Given their chemical and mineral composition, which is similar to natural sand, tailings are the main ingredient in paste preparation. Based on examined chemical compositions of tailings that collected from over ten mines in China, Fig. 4 shows the ternary phase diagrams of different ore types. It is evident that the chemical properties vary between different metal mine tailings and between tailings and Portland cement active materials. The use of paste filling technology for tailings disposal has evolved into both a national strategic initiative and an enterprise survival requirement.

(2) Particle size gradation. The percentage of fine particles in tailings is rising as a consequence of advancements in mineral processing technology. Ref. [34] outlines the tailings grading attributes of several domestic and foreign miners. The presence of fine particles often leads to issues including a slow sedimentation rate of tailings mortar, difficulties in dehydration, low quality of the filling body, and extravagant filling costs. However, full tailings can be effectively used for paste filling. This is especially true for ultrafine tailings, which can generate a high-concentration paste that requires no dehydration and exhibits high strength. This process can significantly reduce filling costs. For instance, the application of paste filling at the Huize lead–zinc mine has successfully reduced the tailings stockpile. The implementation of this process not only protects the environment but also yields significant social benefits.

3.1.2. Cementing material

Cementitious materials used in paste filling account for 30%–70% of the direct filling cost. The use of conventional Portland cement, while costly (approximately 300–500 yuan/t), also falls short in effectively cementing ultrafine tailings. In addition, the production process for this type of cement is linked to several environmental protection concerns, including the excavation of a large number of natural clay minerals, vegetation destruction, and carbon dioxide emissions. Cement production contributes to 10% of China's total carbon emissions in China, with the manufacture of each tone of clinker resulting in approximately 0.85–0.90 tons of carbon dioxide [35]. Therefore, a key development direction for fostering long-term growth involves utilizing solid waste with potential pozzolanic activity to prepare mine filling cementitious materials. This approach significantly reduces the cost of filling material and promotes high-value utilization of solid waste, lowers carbon emissions, safeguards the environment, and provides other comprehensive advantages. The author summarizes several common filling cementitious materials for metal mines, including:

(1) Metallurgical slag cementing materials. Metallurgical waste slag, a by-product of the metal smelting industry, can be transformed into supplementary cementitious materials (SCMs). This can be achieved through grinding and alkali activation of various types of slag, such as blast furnace slag, converter steel slag, lead and zinc slag, copper and nickel slag, magnesium slag, and more. These SCMs can then partially replace cement or form a new type of backfill cementitious material. The most widely used material of this kind is characterized by its broad range of applications, high production volume, and low cost. Currently, the most prevalent cementitious materials achieving industrial applications are those based on mineral and steel slag. These materials also have the potential to reduce the cost per ton of cementitious materials by 30% to 50% [36].

(2) Chemical slag cementing materials. The main waste residues of the chemical industry can be used as raw materials to prepare SCMs or create new cementing materials. Common slags include phosphogypsum, red mud, phosphorus slag, and carbide slag. However, producing commonly used filling cementing materials from this type of slag presents challenges due to its typical concentration in certain areas and its frequent association with strong alkalis, hazardous compounds, and other conditions. Yet, it is the paste filling technology that makes the disposal and use of this type of slag possible. For instance, Kaiyang Phosphate Mine has overcome technical issues associated with phosphogypsum filling by mixing cement, fly ash, and phosphogypsum in a mass ratio of 1:1:(4 − 10) to create a paste with excellent fluidity and high strength [37].

(3) Electrothermal slag cementing material. The main ingredients for creating filling cementitious materials are fly ash, slag, and ash solid waste that stem from thermal power generation and incineration. Fly ash is the most commonly used in practical applications. Despite the wide availability of this type of slag, its quality and activity are low, and the early strength development of the filling body tends to be slow. Thus, it is typically used as an active auxiliary material for filling cementitious materials to reduce costs.

(4) Tailings cementing materials. Fine-grained tailings such as natural phosphogypsum, iron tailings, and gold tailings are mainly used as iron and silicon supplement materials during cement preparation. They can also replace clay in the cement clinker preparation process, improve grinding performance, and promote the sintering process. The production of cementitious materials from these tailings can provide additional nucleation sites, promote hydration reactions, and improve long-term strength [38].

Mechanical excitation, thermal excitation, alkali excitation, salt excitation, carbonization excitation, composite excitation, and coupling excitation are some of the excitation methods and modification principles for the excitation of low-carbon and cost-effective filling materials [39]. A suitable excitation method should be designed according to the physicochemical properties, application scenarios, and cost control of the slag. Additionally, the mechanism of action should be

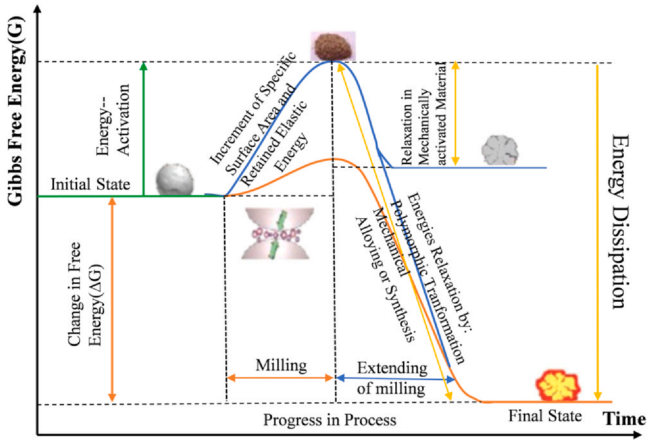

Fig. 5. Schematic diagram of the principle of mechanical grinding to stimulate particle activity. Reproduced with permission from Ref. [40]. Copyright (2020) Elsevier.

summarized and revealed. For example, the literature [40] summarizes the principle of mechanical excitation from the perspective of Gibbs free energy, as shown in Fig. 5.

Key technologies and research directions in the development of new filling cementitious materials include the activity evaluation, excitation principle, regulatory mechanism, performance test, production process, and standardization construction of various slags.

3.1.3. Modification agents

Cemented paste backfill involves the use of additives such as early strength admixtures, water reducers, pumping agents, and inhibitors. The main objectives of these additives are to reduce the water content of the paste, improve its mechanical properties, regulate the hydration reaction, reduce cracking, and increase the resistance of the paste to sulfates, chemicals, and frost. Table 1 provides a comprehensive list of commonly used modifiers categorized by their different functions. A detailed explanation of these modifiers can be found in Ref. [41].

3.2. Tailing thickening technology

Tailing thickening technology is a crucial method for significantly increasing the concentration of tailings slurry through effective solid–liquid separation, a fundamental prerequisite for mine paste filling. Tailings thickening mainly includes gravity thickening and mechanical filtration. Although mechanical filtration can yield filter cake tailings with low water content (solid content of 80wt%–85wt%), it is often associated with high costs and low efficiency. On the other hand, gravitational thickeners have experienced rapid development, evolving from traditional thickeners to high-efficiency thickeners and deep-cone thickeners. As a result, the underflow emission concentration has increased from 40wt%–50wt% to 70wt%–80wt% [42].

Given that full tailings particles are ultrafine and superviscous, tailings mortar remains in a suspended state, and the particles settle very slowly. Moreover, a significant amount of water trapped in flocs is difficult to discharge after the flocs settle quickly owing to the addition of flocculant. The application of deep-cone thickener can address these issues. Deep-cone thickening technology has become the mainstream process of paste preparation owing to its continuous, stable, and efficient advantages. First, full tailings particles are mixed with the flocculant in the feed well to form flocs, facilitating rapid settlement. The combined action of the mud layer pressure and the rake shear force then results in a high concentration of underflow when the flocs settle to the lower section and release their water. Therefore, efficiently mixed flocculation in the feed well [43] and deep dewatering under the combined action of multiple fields [44,45] are key to tailings thickening technology.

Owing to the complexity of the factors affecting the thickening effect, theoretical models often struggle to cover all effects, leading to a significant deviation between theoretical research and practical application. Physical simulation experiments can help understand the tailings thickening process and analyze the key influencing factors, providing an effective means to study tailings thickening. Currently, China's tailings thickening experimental research has formed a complete hierarchical structure, including a series of small dynamic thickening experimental systems (with a diameter of 0.1–0.5 m and a height of 1.5 m), semi-industrial medium-sized deep-cone thickening systems (with a diameter of 1.375 m, and a height of 2.5 m), and industrial large-scale deep-cone thickening test systems (with a diameter of 1.0 m, and a height of 6.0 m). Each system has its advantages and limitations. For instance, while the small dynamic thickening system is flexible and consumes fewer materials, its experimental repeatability is low, and data variation is significant. Conversely, the medium-sized thickening system provides stable experimental data and reliable results, but its height-diameter ratio is small, limiting the experimental range. The large-scale deep-cone thickening system allows for multi-parameter continuous monitoring and multi-factor comprehensive analysis, offering industrial-level guidance. In addition, advancements in computer and numerical simulation technology have made the migration law of tailings and flocs in deep-cone thickeners increasingly transparent. The analysis of the internal structure of deep-cone thickeners by numerical simulation technology has become an essential way to explore the thickening law.

3.3. Paste mixing technology

Paste mixing technology is a process that combines multiscale inert materials, such as waste rock, with active materials (such as cement) and modified materials (such as pumping agents) into a high-concentration tailings mortar. The action of mixer blades facilitates the axial circulation and radial convection of the material [46], ensuring the discrete material is fully dispersed. This results in the homogenization of the filling slurry, thereby improving the transportability of the slurry and the strength performance of the filling body [47].

Table 1
Classification and properties of paste modifiers. Reproduced with permission from Ref. [41]. Copyright (2021) Elsevier.

Performance	Additives
Decreased permeability	Latex, calcium stearate
Improved pumping capability	Organic and synthetic polymers, organic flocculants, organic emulsions, paraffin, coal, asphalt, acrylic, bentonite, silica and hydrated lime
Retarders	Lignin, borax, sugars, tartaric acid and salt
Increasing the flowability of cement paste, reducing the water-to-cement ratio	Naphthalene formaldehyde, lignosulfonate materials, polycarboxylate, superplasticizers, water reducers
Accelerators and primary resistance boosters	Sodium, calcium formate, calcium nitrite, calcium nitrate, calcium silicate, triethanolamine, thioxyanate
Air-entraining agents	dibutyl phosphate, octyl alcohol, insoluble carbon esters and boric triethyl phosphate
Improves resistance to freezing	Salts, wood resins, some synthetic detergents, lignin sulfonic salts, petroleum salts, fatty acids and resins and their salts, alkyl benzene sulfonate, hydrocarbon sulfate salts
Strong cement paste to place underwater	Cellulose, acrylic polymer

A defining characteristic of paste is its high concentration. Ultrafine binder particles, such as cement, tend to agglomerate and are challenging to disperse in high-concentration slurry [48]. Unlike intermittent concrete mixing, paste mixing frequently uses a continuous mixing method, meaning that loading, mixing, unloading, and other procedures occur seamlessly. Each mixture is introduced at one end of the mixing apparatus, and the paste is pushed from the other end through the machine's internal mixing mechanism without any interruption.

Commonly used continuous mixing equipment includes horizontal mixers, vertical mixing barrels, and high-speed activation mixers [49]. By generating strong local turbulence, vertical stirring disrupts the internal balance of the slurry, ensuring the uniform mixing of various materials. Its strengths lie in the homogeneous quality and high activation impact it produces. However, when dealing with high concentrations, the load is substantial, leading to rapid rotor wear and poor adaptability. By contrast, horizontal stirring utilizes spiral blades, which afford many contact points with the slurry and exert a large mechanical force, making it suitable for high-concentration stirring with coarse aggregates. Presently, two-stage horizontal continuous stirring is the most prevalent paste stirring method. For instance, in the Jiashi Copper Mine, a constant high-liquid-level stirring method was designed for high mud and high viscosity paste. This method optimizes the mixing direction and rate, causing the slurry to create a circumfluence movement. This ensures optimal mixing time, eliminates the mixing blind area, and solves the problem of cement agglomeration. Under the same cement–sand ratio, this approach increased the 28-d strength of the filling body by 66% [50]. After the initial mixing in a biaxial mixer or a stirring tank, the homogenization mixing effect can be further improved using a high-speed activation mixer. The high-speed activation mixer can exert a powerful mechanical effect, causing cement particles to collide with each other and constantly expose new surfaces. This strengthens the hydration of cement, ultimately producing a homogeneous paste slurry with excellent fluidity. In addition, some horizontal and vertical mixers used in the concrete industry can also be adapted for paste backfill applications. Horizontal mixers, such as drum mixers and paddle mixers, and vertical mixers, including pan mixers and planetary mixers, can be tailored to meet the specific requirements of mixing paste slurry, enabling operators to achieve efficient and effective mixing of backfill materials.

3.4. Paste pipeline transportation technology

Paste pipeline transportation mainly adopts two methods: pump pressure transportation and gravity transportation. Unlike traditional low-concentration graded tailings slurry, paste differs significantly in terms of material composition, solid content, and particle size distribution. This makes its flow performance more complex and poses a considerable challenge in predicting and calculating pipe flow resistance.

The first step is to establish a prediction model for tube resistance that is suitable for paste. Early formulas for calculating frictional resistance were based on solid–liquid two-phase flow theory. These include the Jinchuan formula, Changsha Mining and Metallurgy Institute formula, Anshan Institute formula, and Huize empirical formula. However, these formulas were developed for specific materials and application environments, limiting their applicability [51]. Recent research indicates that frictional resistance is affected by many factors, such as concentration, aggregate gradation, density, pipe diameter, flow rate, and additives. Additionally, paste transportation via pipelines exhibits thixotropy, pipe wall slip characteristics, and significant temperature effects.

The second step involves designing a logical and scientifically sound pipe network layout and selecting an appropriate mode of transportation. When using gravity transportation, the most important thing to consider when designing an optimal filling pipe network is achieving a full-flow state, maximizing the use of the residual potential energy of the slurry in vertical pipelines, and minimizing pipeline impact damage. When employing pump pressure conveyance, it is crucial to choose a positive displacement pump compatible with the paste. Plunger pumps are commonly used in this context [52]. Simultaneously, the use of specific pumping agents can significantly reduce the yield stress and viscosity of the paste, thereby substantially decreasing pipe resistance [52].

Furthermore, the maintenance of the pipeline, including regular flushing and cleaning, is vital to prevent blockages and ensure the smooth flow of paste. Pipeline cleaning includes clear water flushing and air-water combined flushing. Clear water flushing involves using a high-pressure flow of clean water to remove sediments from the pipeline. This method is straightforward but requires a large volume of water. On the other hand, air-water combined flushing introduces compressed air along with water into the pipeline, creating a turbulent flow that effectively removes more stubborn deposits. This technique uses less water and generally achieves better cleaning results compared to clear water flushing. Developing a well-designed pipe network to efficiently transport high-concentration and high-viscosity paste to the stope is also crucial. It is important to avoid designs that include uphill sections and excessive bends in the pipes. Additionally, incorporating emergency valves can allow for quick response to accidents or pipeline failures.

Lastly, monitoring the state of the pipeline and paste transportation is critical. This includes regular checks of pipeline wall thickness, diagnosing and providing early warnings for pipeline blockage and leakage based on changes in flow and pressure [53]. In addition, daily trials such as measuring rheology, slump, solid concentrations, and pressure, as well as temperature and strength monitoring, are essential for better control of paste manufacturing and delivery to the stopes. These measurements help optimize the paste's properties and ensure a smooth and efficient delivery process.

In summary, the successful long-distance pipeline transportation of paste relies on accurate prediction of pipeline transportation resistance, the use of new paste plunger pumps, specific pumping agents for paste, and technology to diagnose pipeline blockage and leakage.

3.5. Macroscopic and mesoscopic mechanical properties of pastes

The mechanical characteristics of the filling body are among the most important indices in engineering applications, directly impacting the cost, efficiency, and safety of mining operations. The research on the mechanical properties of paste mainly includes the strength demand theory of paste, the multifield coupling curing mechanism and regulation mechanism of paste, its role in the stope, the prediction model of mechanical properties, and *in-situ* monitoring of paste properties.

3.5.1. Macroscopic mechanical properties

The macroscopic mechanical properties of the paste usually refer to the uniaxial compressive strength. Both internal and external factors significantly influence paste strength. Internal factors refer to the paste concentration and the cement-to-sand ratio, tailings gradation, the type of cementitious material, and any admixtures used. External factors, on the other hand, include the curing temperature, curing time, and the operational environment [54]. The strength design of paste is specific to each mine, depending on the specific mining technical conditions and mining process requirements. Various technical issues need to be considered when determining an appropriate strength value. These include mining technology, filling technology level, filling material properties, and economic factors such as mining costs and benefits. Table 2 showes the general selection range of backfill strength for different mining methods.

3.5.2. Microstructure analysis

The evolution of microstructure during the hydration and hardening process of the paste determines the macroscopic mechanical properties

Table 2
Filling body strength selection table of different filling mining methods.

Filling method	Function of the filling body	Filling body strength / MPa
Mining along strike the upward layered backfill method, point pillar backfill method	(1) Ensure self-propelled equipment running; (2) the bottom of the stope requires high strength, which is an artificial bottom pillar or artificial roof.	Surface: 1–2; others: 0–0.5; artificial sill pillar: 4–5.
Upward drift filling mining method	(1) Ensure self-propelled equipment running; (2) ensure that the filling body does not collapse when the adjacent route is mined; (3) the first and second layers have high strength requirements.	Surface: 1–2; others: 0–1; layers 1 and 2: 4–5.
Downward drift filling mining method	(1) Ensure the safety of operation under an artificial false roof; (2) ensure that the filling body does not collapse when the adjacent route is mined.	False roof: 4–5; others: 1–2.
Wall fill method	Ensure that the filling body does not collapse when the adjacent route is mined.	0–0.6
Sublevel fill method	(1) Ensure that the filling body has a larger natural angle of repose; (2) individuals do not collapse when making false lanes.	0–1 or 2–4
Inter-column to be recovered by level filling method of backfill body	(1) The allowable exposed area of the backfill body is more than 1500–2000 m^2; (2) the backfill body can stand on its own before the end of mining.	Ordinary conditions: 1–2; high-level stope: 1–4.

of the paste. It also serves as the foundation for studying the hydration, hardening mechanism, and performance control of pastes. Research on the microstructure characteristics of paste mainly focuses on the following aspects:

(1) Hydration characteristics research. The hydration heat, phase types, and number of hydration products present in the paste's cementitious materials under different curing times and environments were analyzed using tools like microcalorimeters, X-ray diffraction, and thermogravimetric analyzers. These methods help unveil the hydration mechanism of cementitious materials, establish the hydration kinetic equation of paste, and explain the water hardening mechanism of paste.
(2) Microscopic morphology research. High-resolution optical microscopes and scanning electron microscope (SEM) allow for the observation of the microstructure and structure of microsized paste, enabling analysis of the hydration products and pore distribution at different stages. In particular, when combined with an energy-dispersive spectrometer, SEM can determine the distribution of each phase in the microstructure, providing a microscopic quantitative method for verifying the relevant mechanism research.
(3) Pore structure research. The pore structure of the paste is intimately associated with the mechanical properties, ion permeability, and deterioration properties of the paste. At present, mercury intrusion porosimetry, computed tomography (CT), and low-field nuclear magnetic resonance (NMR) are commonly used to study the pore structure. The mercury intrusion porosimetry measures the pore volume and pore size distribution by pressing mercury into the paste. CT and NMR offer a new and widely used method for studying pore structure characteristics, allowing for non-destructive detection and 3D reconstruction of the pore structure [19]. Fig. 6 shows several common methods for studying the paste microstructure.

3.6. Paste in-situ performance monitoring technology

The ultimate purpose of cemented paste backfill is to serve mining safety and improve resource recovery efficiency. However, once the paste reaches the goaf, a "black box" maintenance period begins, where fluid–solid transformation and mechanical development processes become complex and unpredictable. These uncertainties can significantly impact mining safety and efficiency [55]. *In situ* performance monitoring technology is used to monitor the multifield performance of the backfill during solidification and gauge the long-term mechanical properties of the filling body. This approach helps to determine the backfill status within the goaf timely, providing crucial data for refining the filling ratio and precision of mining strategies. Additionally, it offers early warnings about the strength of the filling body, thereby ensuring the structural safety of the filling body.

The curing process is a multifaceted phenomenon involving simultaneous multifield performance, serving as a critical link between the "hydration reaction" performance [56,57]. Current research primarily employs indoor backfill column experiments to simulate real stope conditions. Sensors are used to monitor the multifield performance (including matrix suction, volumetric water content, conductivity, and temperature) of the backfill curing process over time [58]. By analyzing the data collected by these sensors, researchers can study the evolution of multifield properties under different influencing factors at various maintenance times. This analysis also reveals how multifield properties evolve under different factors at the same maintenance time. When combined with the results of the microanalysis, these findings enable a comprehensive understanding of the strength development mechanism of the backfill test block and the evolution mechanism of multifield properties. This approach provides insights into the intrinsic mechanisms governing both the strength and multifield properties of backfill. We analyze the strength of the filled body specimens, explain the intrinsic hydration mechanism, and the evolution mechanism of the pore structure and other microscopic effects, and characterize the strength of the filled body by combining the multifield properties such as matrix suction, volumetric water content, temperature, and electrical conductivity. We also establish a multifield performance–strength synergistic characterization model [59]. Fig. 7 presents an industrial experimental monitoring device designed to measure thermal–hydraulic–force–chemical multifield properties during the curing process [60,61], which can be used for both monitoring the multifield properties of the backfill and the pressure of the barricade. This device and method overcome the "black box" maintenance of the traditional backfill body, enabling transparent maintenance of the stope backfill body. This advancement ensures the safety of the backfill structure and the backfill efficiency.

3.7. Backfill barricade construction technology

Barricade construction is an indispensable part of the cemented paste backfill process. The duration of stope filling largely hinges on factors such as the geometry and size of the stope, as well as the cementing time. Notably, the stope barricade plays a significant role in affecting filling efficiency. The pressure-bearing capacity and thickness design of the barricade are paramount for enhancing filling efficiency and ensuring well safety [62].

Barricades can be classified into several types based on different materials and construction processes. These include concrete, red brick, steel structure, molded bag, self-constructed with filling materials, 3D printed, mechanized, and flexible barricades [63]. Concrete and red brick barricades [64] are commonly used, while molded bag [65] and 3D-printed barricades [66] represent newer construction techniques. Given that cemented paste backfill solidifies quickly and does not require urination, flexible barricades have gained popularity in mines

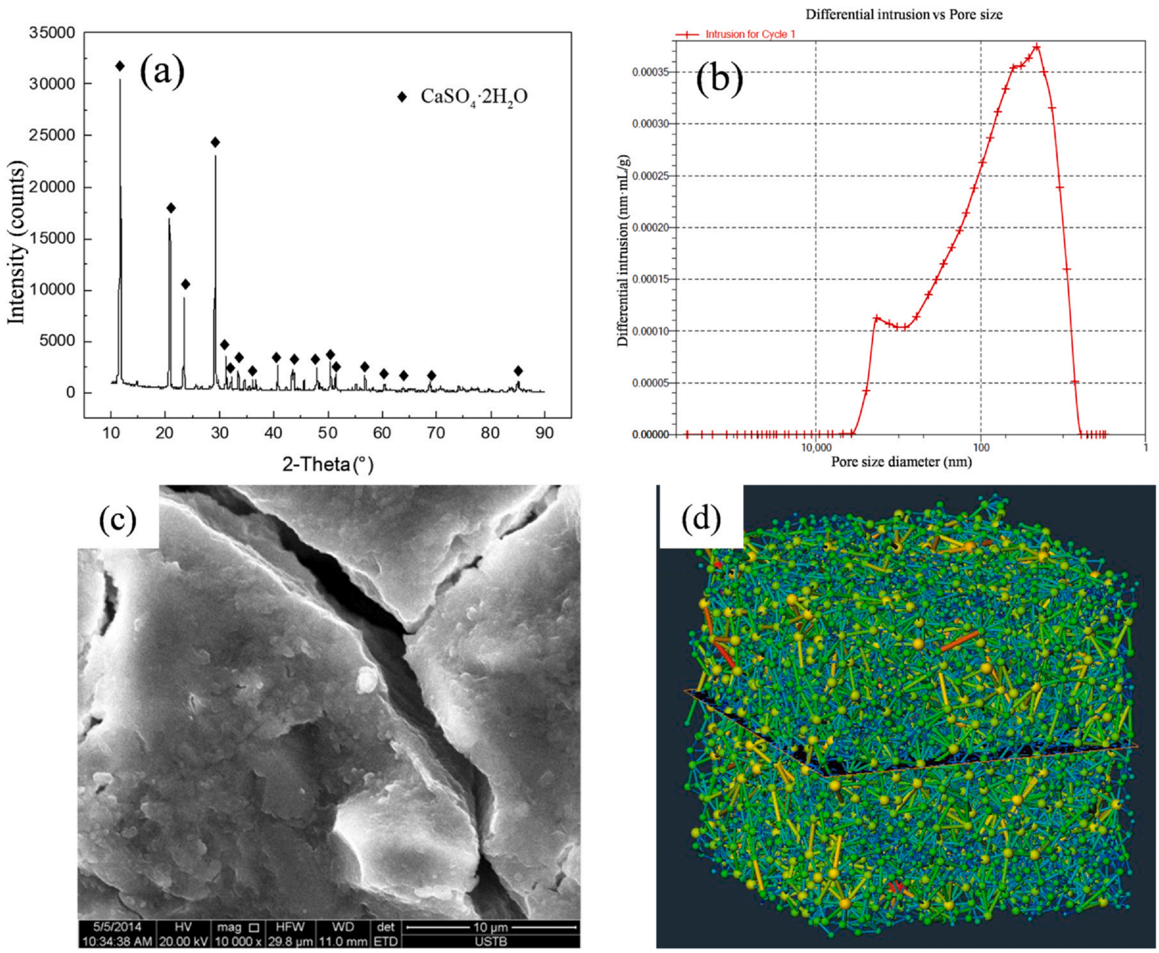

Fig. 6. Common test methods of paste microstructures: (a) X-ray diffraction pattern; (b) mercury injection porosimetry laboratory results curve; (c) scanning electron microscope appearances; (d) CT 3D reconstruction of pore structures.

owing to their ability to balance the production cycle, cost, and material recycling, as shown in Fig. 8. Considering the frequent need for personnel to enter the goaf during barricade construction, mechanized construction of barricades is projected to be the future trend in mine barricade construction for safety reasons [67].

3.8. Intelligent control technology of cemented paste backfill

The cemented paste backfill process is characterized by multi-timescale and multivariable coupling, making manual decision-making accuracy challenging. At the same time, the personalized design of the equipment in the cemented paste backfill process makes it difficult to achieve synergy, interoperability, and linkage between different devices. To address these challenges, systems based on distributed control systems (DCSs), programmable logic controllers (PLCs), or a hybrid control system consisting of DCSs and PLCs are utilized. These systems employ automated equipment and instruments to control the whole chain, from tailings release quality, proportioning quality, mixing quality, transporting quality, and stope filling quality. This approach enables fine proportioning of filling materials, automated control of the filling process, and instantaneous feedback on filling parameters. Furthermore, artificial intelligence technology is integrated into the design, operation, monitoring, and early warning of cemented paste backfill. This integration serves to reduce or even eliminate the randomness and hysteresis effects caused by human monitoring and correction. As a result, several advancements have been made, including the development of data-driven accurate prediction for paste filling parameters [68–70], image recognition-based intelligent technology for paste concentration [71–73], monitoring and visualization technology for filling status [74], and a one-key intelligent paste filling system [75]. These technological innovations facilitate intelligent decision-making regarding filling schemes, intelligent sensing of filling states, and intelligent control of the filling process [76].

3.9. Numerical simulation technology for the whole process of cemented paste backfill

Cemented paste backfill involves a series of processes, such as deep-cone thickening, paste mixing, pipeline transportation, and stope curing. To gain a more comprehensive understanding of the performance response laws inherent to these processes, numerical simulation can be used as a supplement to experimental data. Numerical simulations of deep-cone densification are crucial for designing feeding wells and understanding both particle transportation and concentration distribution within the deep cone. Typically, CFD (computational fluid dynamics) software is used for these simulations. The numerical simulation of the paste mixing process provides valuable insights into material homogenization. It can aid in effective blade design and help avoid blind spots during mixing. DEM (Distinct Element Method) software is generally the tool of choice for these simulations. Simulating paste pipeline transportation plays a crucial role in optimizing pipeline resistance and design. Fluent software is commonly used for these simulations. Once the paste reaches the stope, the curing process begins. This involves the evolution of multifield performance under various effects. Numerical simulations can provide a comprehensive understanding of the entire paste curing situation within large volume stopes.

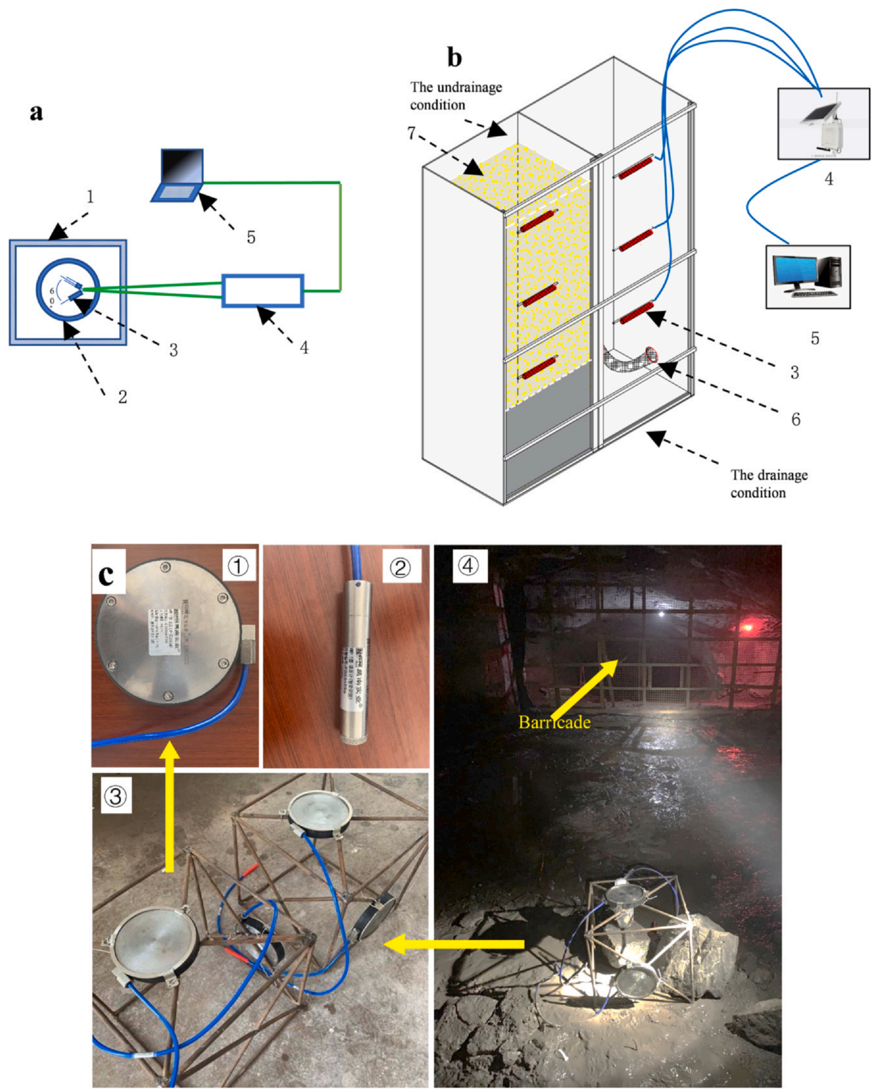

Fig. 7. Indoor-semi-industrial-real quarry paste multifield *in-situ* performance monitoring: (a) monitoring device modified from [60]; (b) similar simulation device; (c) sensors and the installation: ① total stress sensor, ② pore water pressure sensor, ③ the total stress sensor fixed at a steel frame, and ④ the sensors arranged in the stope. In Fig. 7a and b, 1 is the curing device box, 2 is the filling box, 3 is the sensor, 4 is the data collector EM50, 5 is the calculator, 6 is the drain, 7 is the filling material. (b, c) Reproduced with permission from Ref. [61]. Copyright (2022) Elsevier

Fig. 8. Physical drawing of cemented paste backfill flexible barricade construction.

For this purpose, Comsol software is typically used. The key to successful numerical simulations of the whole cemented paste backfill process lies in constructing a stable and reliable mathematical model. Such simulations hold significant value in visualizing and enhancing the intelligence of cemented paste backfill.

The field of numerical simulations for the whole process of cemented paste backfill has seen significant contributions from numerous scholars, each applying different software tools to their research. For instance, Wu *et al.* [77] used CFD and a population balance model to study the particle size distribution (PSD) and underflow concentration in a deep-cone thickener. The team explored the effects of various factors, such as rake frame speed, feed flow rate, and feed slurry concentration, on PSD and underflow concentration, grounding their research in practical production scenarios. Li *et al.* [78] established a discrete element model of paste using the Hertz–Mindlin with JKR contact method. From this, they constructed a numerical model of the two-axis screw conveyor to investigate how different process parameters affected the degree of paste mixing. Based on Fluent software, Yan *et al.* [79] investigated the motion law of coarse aggregate particles using a macro particle model. He treated the full tailings paste slurry as a pseudo-homogeneous suspension and developed a composite flow model with shear and non-shear flow zones based on the flow velocity distribution characteristics observed during pipeline transportation of coarse aggregate paste. Cui and Fall [80,81] developed a heat–water–force–chemical multifield coupling model, which fully considered the effects of hydraulic and chemical processes on the temperature

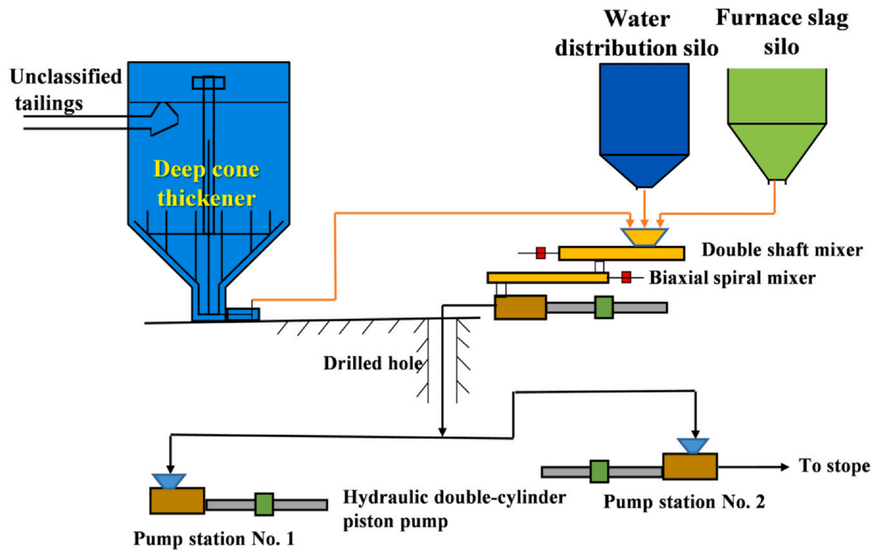

Fig. 9. Paste pumping backfill system of Huize's lead–zinc mine.

change during the curing process of cemented paste backfill. For mechanical processes, an elastoplastic model was incorporated into the heat–water–force–chemical model. Furthermore, the model accounted for the effects of cement hydration on backfill properties, including permeability, thermal conductivity, and cohesive force. These studies collectively contribute to the construction of stable and reliable mathematical models related to cemented paste backfill. Such work continually advances the visualization and intelligent development of cemented paste backfill through numerical simulations of its entire process.

4. Green mining technology based on cemented paste backfill

4.1. Lead–zinc mine in Huize, Yunnan Province, China

In 2006, the Huize lead–zinc mine successfully completed the industrialized test of paste filling and started industrialized production. The implementation of the paste filling system allowed all tailings from the beneficiation process to be filled into the underground goaf. This not only saved on new tailings pond construction costs but also addressed environmental pollution issues and concerns about occupied farmland caused by mining wastes. By doing so, it achieved a comprehensive utilization of resources and met clean production standards, aligning with the principles of green mining development.

The conditions at the Huize lead–zinc mine are extremely complex owing to the deep burial of the orebody, highly fragmented ore rock, high-grade ore, and small scale of the deposit [82]. With the orebody buried more than 1000 m below the surface and situated in the Yunnan–Guizhou Plateau's canyon area, the original rock is under high stress. Mining activity further exacerbates this, causing stress concentration in the surrounding rock and leading to increased rock damage. Occurrences of small-scale rock explosions have been reported in some sections of the roadway. Moreover, the mine location in a V-shaped deep canyon terrain of the Niulan River poses topographic constraints that prevent the expansion of the existing tailings point and smelting slag dump. The selection of new sites for these facilities proves challenging. Additionally, the mine is located within an ecological protection zone in the middle and upper reaches of the Yangtze River, where industrial waste discharge is strictly limited. Therefore, deep resource development must consider these factors and provide proper solutions for tailings and smelting slag. The full tailings sand–water quenching slag paste filling, which adheres to the technical requirements of waste-free mining and mining process technology for mine filling, is a fundamental solution to these challenges. It allows for an efficient and enhanced mining method. The paste pumping filling system used at the Huize lead–zinc mine ensures no tailings discharge on the surface, while the supporting effect of the filling body ensures the safe and efficient mining of deep resources. The system uses a two-stage mixing slurry preparation process, with a paste flurry concentration of 78wt%–80wt%, a slump of 20–26 cm, and a filling capacity of 60 m^3/h. The filling materials consist of full tailings, water quenching slag, and cement. The mass ratio of full tailings to water-quenched slag is 3:1, and the mass ratio of full gray-sand (cement : (full tailings + water-quenched slag)) ranges from 1:4 to 1:16. The paste pumping and filling system of Huize lead–zinc mine is shown in Fig. 9.

4.2. Jinchuan Nickel Mine, Gansu Province, China

The construction of China's first paste filling system began in 1994 in the Jinchuan No. 2 mining area and was completed in 1999. This pioneering system included two stages of filtration and dewatering, two stages of mixing, preparation, and pumping, among other key process pumping stations. Following the system launch, various technical issues arose, prompting Jinchuan Company to organize a series of technical modifications. These adjustments included the removal of the filter and the adoption of the tailings silo cycle slurry for tailings dewatering. By the end of 2008, these changes allowed the system to reach its design production capacity. However, issues with the stability of the tailings discharge concentration persisted in the slurry production of tailings silos. Combined with the complexity of the filling pipe network, these challenges ultimately led to the discontinuation of the system in 2014. A collaborative effort was initiated in 2017 by Jinchuan No. 2 Mine, the University of Science and Technology Beijing, and Jinchuan Nickel Mining: the development of a full tailings–waste rock combined paste filling system with deep-cone thickening at its core [83]. The successful construction of this new system was completed in 2021, as shown in Fig. 10. Based on the results of rheological experiments, the final design of the paste concentration is between 77wt% and 79wt%. The cement-to-tailings mass ratio is 1:4, and the tailings-to-waste rock mass ratio is 4:6. The key equipment includes a 16-m deep-cone thickener, a 6-m^3 two-stage continuous horizontal mixer, and an S-valve filling plunger pump. The system achieves a slump degree greater than 23 cm, a 7-d strength exceeding 3 MPa, and a 28-d strength surpassing 5 MPa.

4.3. Chambishi Copper Mine in Zambia

The Chambishi Copper Mine in Zambia, one of the three major ore bodies owned by China Nonferrous Mining Co., Ltd., is a newly built mine that began operations in 2018. Construction of the paste filling

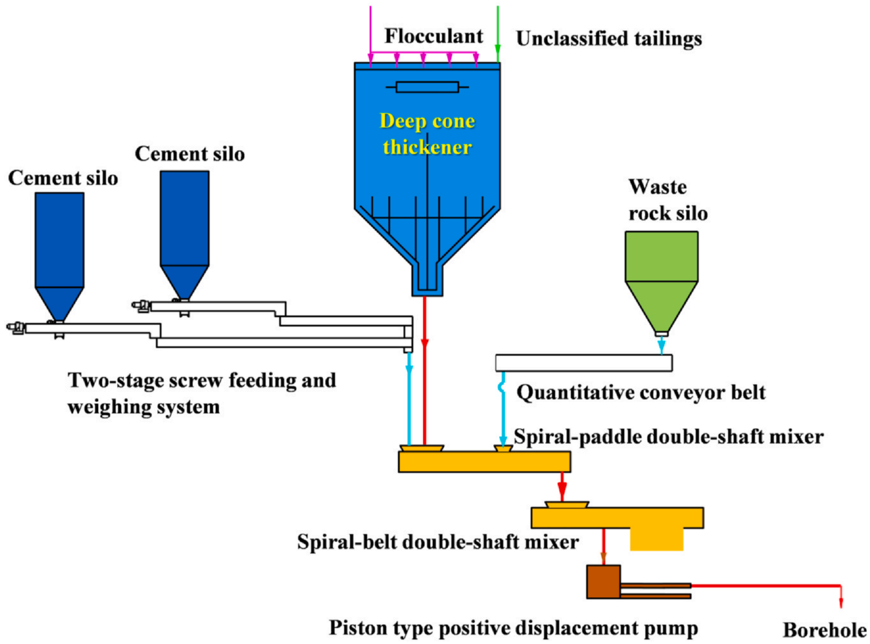

Fig. 10. Co-disposal cemented paste backfill system.

system started in June 2015 and involved various states, including experimentation, preliminary design, construction design, system construction, standalone operation, and linkage test run. After more than four years of joint technical research, the system was successfully commissioned in December 2019. The implemented paste filling system in the southeast ore body of Chambishi Copper Mine, shown in Fig. 11, is unique as it combines high-flow paste autoflow filling with long-distance high-concentration tailings discharge. This innovative approach was proposed as an industrial test idea of the paste filling system, termed "opening process–enhancing concentration–improving strength" [84]. The filling concentration was ultimately achieved at 70wt%–72wt%, with a cement-tailings mass ratio of 1:8.6 and a filling strength of 28 d exceeding 1 MPa. This successful application represents another breakthrough for China's paste technology on a global scale, and the system is now fully operational, providing strong support for the mine's capacity to meet standard, safe, and efficient mining protocols.

A significant feature of the paste filling process at this mine is its dual functionality. It meets the requirements for paste filling in km-deep wells and facilitates 15-km long-distance high-concentration surface tailings discharge. This has led to the creation of a new full tailings paste filling system and tailings discharge system [85]. The system primarily consists of whole tailings, all of which are transported to two thickeners in the paste filling preparation station by slurry pumps.

Each thickener has a diameter of 18 m, a total height of 16.6 m, a cone angle of 30°, and a processing capacity of 5000 t/d. It can handle a maximum underflow flow rate of 165 m^3/h and a maximum underflow concentration of 72wt%. The system's dewatering capacity and pump pressure conveying capacity exceed 200 m^3/h, and it features a 10 m^3 volume mixer with a mixing capacity of 180 m^3/h, which is the largest reported horizontal mixer of its kind domestically and internationally. By adopting a liquid level lifting and stabilizing device with independent intellectual property rights, the system achieves homogeneous mixing technology for fine-grained full-tail paste with high

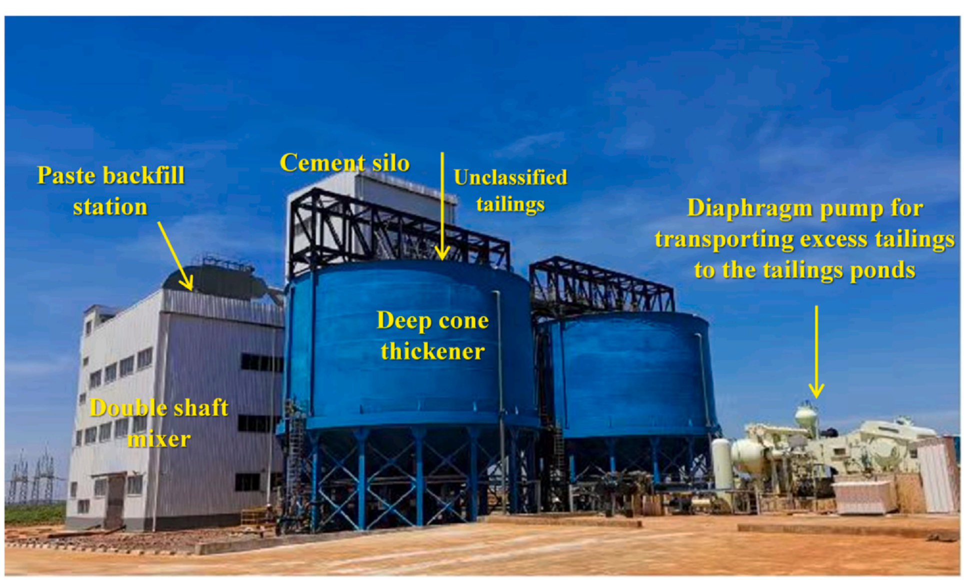

Fig. 11. Appearance of the paste backfill system of the Chambishi southeast orebody.

liquid level and reversed peripheral flow. The cement silo adopts 2 sets of storage silos, each with a rectangular section and conical bottom structure with a volume of 832 m^3, and employs micro powder weighing for measurement. The highly concentrated tailings prepared by the thickener are transported into the mixer by the underflow pump and mixed with cement to produce the full tailings cemented paste filling material, which is then transported to the stope for filling by the pipe with an inner diameter of 175 mm.

Given the challenges presented by the deeply buried ore body, extensive theoretical calculations and verifications were conducted. These led to the bold use of self-flow transport. When the filling concentration reached 72wt% and the yield stress exceeded 100 Pa, this method facilitated the self-flow transportation of paste over a distance exceeding 2000 m. This achievement was made possible by harnessing the combined power of self-weight potential energy and "negative pressure siphon." Any surplus high-concentration tailings is efficiently transported to the tailings pond through 3 sets of diaphragm pumps (2 in operation and 1 on standby). These pumps have a remarkable transporting capacity of 265 m^3/h and a transportation pressure of 7 MPa, facilitating material movement over a distance of approximately 15 km. Importantly, this whole process is remotely controlled from the central control room. Key parameters, including flow rate and concentration, are accurately measured using a nuclear densitometer and Sondar ultrasonic flowmeter.

5. Conclusion and prospects

Cemented paste backfill technology, having been utilized in China for more than 20 years, has shown rapid development. It has evolved from its initial stages to being recognized as an advanced application by various ministries and commissions. As we continue to prioritize green mining, which is the future of metal mines, cemented paste backfill has already established a national standard in China. Despite its maturity, there is still room for further innovation and scientific research in theory, technology, equipment, and modes.

(1) Theoretical aspects: Paste rheology forms the fundamental theory for the whole process of cemented paste backfill. Even though the theoretical framework has been established, future work includes standardizing rheology tests, constitutive equations, micro-mechanisms, and rheological measurement technology.
(2) Technology aspects: Cemented paste backfill technology strongly supports the construction and high-quality development of green mines in China. In the future, the technology will evolve toward a "three-low" direction: low carbon, low energy consumption, and low cost. This could involve the use of low-carbon cementitious materials, short-process low-energy consumption technology, and accurate, refined filling technology.
(3) Equipment aspects: The development of deep-cone thickeners and filling pumps has led to the widespread use and popularity of cemented paste backfill technology in China. Future developments in equipment should aim for intensification, smaller-area requirements, and lower failure rates. Generally, the trend is moving toward more intelligent equipment.
(4) Mode aspects: The main future development mode for cemented paste backfill is the "tailless mine" mode, based on traditional models. This mode can be broken down into two specific aspects: First, for most mines that cannot completely fill tailings and with increasing environmental protection standards disallowing the construction of new tailings ponds, the "fine particle filling + coarse particle utilization" approach will be the first mode of tailless mines. Second, for some smaller mines without processing plants or those generating toxic and harmful tailings unsuitable for filling, "mobile paste filling" will emerge as another development mode.

CRediT authorship contribution statement

Aixiang Wu: Conceptualization, Writing – original draft. **Yong Wang:** Writing – original draft, Writing – review & editing. **Zhu'en Ruan:** Writing – original draft. **Bolin Xiao:** Formal analysis, Writing – original draft. **Jiandong Wang:** Writing – original draft. **Linqi Wang:** Writing – review & editing.

Declaration of Competing Interest

Aixiang Wu and Yong Wang are editorial board members for this journal and were not involved in the editorial review or the decision to publish this article. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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