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Invited Review

Progress and prospects of mining with backfill in metal mines in China

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Abstract: Mining is the foundation of modern industrial development. In the context of the "carbon peaking and carbon neutrality" era, countries have put forward the development strategy of "adhering to the harmonious coexistence of humans and nature." The ongoing progress and improvement of filling mining technology have provided significant advantages, such as "green mining, safe, efficient, and low-carbon emission," which is crucial to the comprehensive utilization of mining solid waste, environmental protection, and safety of re-mining. This review paper describes the development history of metal mine filling mining in China and the characteristics of each stage. The excitation mechanism and current research status of producing cementitious materials from blast furnace slag and other industrial wastes are then presented, and the concept of developing cementitious materials for backfill based on the whole solid waste is proposed. The advances in the mechanical characteristics of cemented backfill are elaborated on four typical levels: static mechanics, dynamic mechanics, mechanical influencing factors, and multi-scale mechanics. The working/rheological characteristics of the filling slurry are presented, given the importance of the filling materials conveying process. Finally, the future perspectives of mining with backfill are discussed based on the features of modern filling concepts to provide the necessary theoretical research value for filling mining.

Keywords: mining with backfill; cementitious materials; mechanical characteristics; slurry properties; future perspectives

1. Introduction

Presently, China's metal mines are mainly in an underground mining mode, and the primary mining methods are divided into three major categories: the caving, filling, and open-stope techniques. The development of the mining industry plays a vital role in the national economy; therefore, the national government and the scientific community have attached great importance to and strongly supported such development. Moreover, they have made great progress in the following aspects: waste-free and environmentally friendly mining technology, open-pit to underground mining transition technology, underground continuous mining technology, complex and hard-exploited ores mining technology, and intelligent mining technology, among others.

Mining gradually shifts to deeper depths due to the continuous decline of utilizable ores at shallow depths [1]. Sixteen metal mines currently operating in China have extended to a depth of more than 1000 m [2]. Deep mines are facing a distinct situation of "three highs and one disturbance" and need to adapt to the requirements of the national mining development strategy [3]. However, the technical level of mining, economic constraints, and historic legacy problems, such as the crude development of underground hard rock metal mines, severely restrict the sustainable and healthy development of mines [4]. The new concept of mining continuously proposed by the government provides a chance for revolutionizing traditional mines. China's 14th Five-Year Plan proposed the "acceleration of the green development of mining," which has led to a gradual transition to focus on the comprehensive use of deep ores, adhere to innovation and coordinated development, and promote the harmonious coexistence of humans and nature [5].

Mining with backfill refills solid waste, represented by waste rock and tailings, into underground void (mined-out) areas, effectively controlling surface subsidence and collapse and reducing mining-induced geological disasters [6]. This technique helps to realize the comprehensive utilization of mining waste, improve the recovery rate of metal/mineral resources, and reduce the depletion rate during re-mining, with the unique advantage of "one filling to cure three wastes and one waste to cure two hazards" [7]. In the context of carbon-neutral carbon peaks, China's 14th Five-Year Plans for the enlargement of the raw materials industry and the construction of waste-free cities put forward the comprehensive utilization of mining waste, such as tailings/waste rock [8] and the promotion of environmentally friendly underground filling of tailings and other industrial solid wastes [9]. This

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shows that the firm trend in the progress of mining is a low-carbon growth of mineral resources employing new technologies and other means [10]. Mining with backfill can help the green development, low-carbon emission, recycling, and viable growth of traditional mines, which aligns with the opportunities and challenges provided by the contemporary concept of ecological civilization [11].

The economic factors, slurry quality, and environmental factors govern the development history of mining with backfill. The economic factor refers to decreased financial profits and increased mining costs due to backfill. The low grade of the metal ore and the large mining depths result in a significant increase in mining costs with increasing depth. Gelling materials are the key to controlling the filling costs and helping innovate filling mining techniques and technologies [12]. The use of cheap waste materials with potential volcanic ash activity to prepare mining gelling materials is a hot research topic in mining with backfill [13]. The slurry quality is important to meet the conveying necessities and filling quality, directly affecting the filling slurry's workability/rheological behavior [14] and whether it can be adapted to the existing fill system and achieve high-quality filling [15]. The environmental factor refers to industry standards and policy directions that are constantly being put forward as the national government and society at large become more aware of environmental shields [16]. When the filling slurry is delivered to the mined-out area, the strength and damage progress patterns of cemented backfill differ remarkably based on the curing process and environment in which it is deposited, the cementing material, and the form of interaction with the nearby rock [15,17]. Hence, in-depth research on the physical behavior of cemented backfill is an operative means to ensure the safe creation and stability control of cemented backfill in underground metal mines.

This review paper first elaborates on China's filling mining development history and analyzes its different era characteristics and specific mine sites. It also carefully examines filling mining in metal mines regarding the progress and preparation of cementitious materials. Moreover, this paper incorporates the physical behavior and liquidity performance of backfilling. Finally, it discusses the change direction of mining with backfill in the emerging era.

2. Development history of filling mining

With the remarkable improvement in filling mining/equipment technology, the continuous development of mining with backfill has been greatly promoted [18]. As a function of the employed materials/methods, the main backfill types can be named as dry, water–sand, cemented, high concentration (H-conc) cemented, cemented paste/tailings, whole tailings cemented paste, and emerging cemented filling [19]. At the same time, each stage of the improvement history of China's mining with backfill has unique features of the times. Fig. 1 shows the progress history of China's mining methods, including backfill.

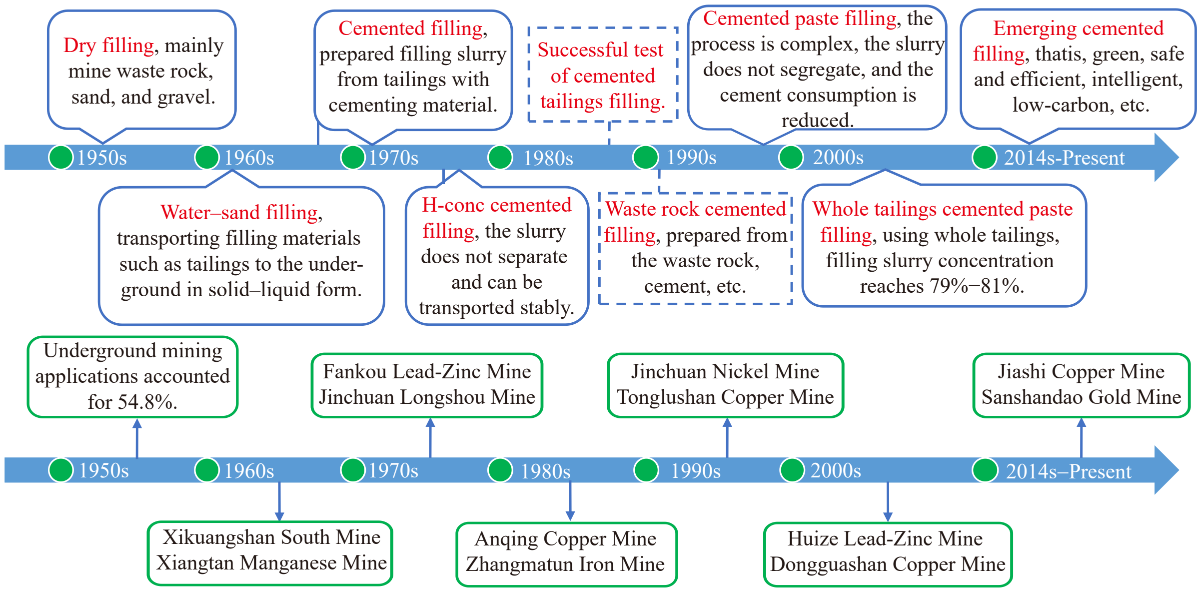

Fig. 1. Development history of China's filling mining methods.

Dry filling is a method used in the early years, whereby waste rock, sand, and gravel were transported to the extraction area through ore trucks, wind, or other mechanical means [20]. In the 1950s, dry filling was used in 54.8% of underground nonferrous metal mines; however, it could not meet the production supplies of "strong mining/extraction/filling," and the proportion of production was reduced to 0.7% by 1963 [20–21]. Water–sand filling refers to transporting filling materials, such as tailings sand and gravel, to the underground in a solid–liquid flow, with a slurry concentration usually lower than 70wt% [22]. In the 1960s, the Xikuangshan South Mine (1965) first adopted the tailings hydraulic filling mining process, which slowed down surface subsidence. The Xiangtan Manganese Mine adopted the gravel hydraulic filling process, which achieved sound prevention effects [23]. The cemented filling usually uses a mix of waste rock, process tailings, and hydraulic binder to prepare filling slurry, which is pumped by pipeline or gravity flow to the extraction zone. The key drivers of this system are to eliminate the difficulties of low strength of water–sand filling and to seriously segregate the filling slurry [24]. The successful use of graded tailings cemented filling at the Fankou Lead-Zinc Mine (1968) signified a fresh stage in the history of China's filling mining. In the 1960s and 1970s, cemented filling required high material gradation and was mainly based on coarse aggregate (e.g., Gobi aggregate, Jinchuan Longshou Mine, cement unit consumption of 200 kg/m^3). In the 1970s and 1980s, fine sands (e.g., tailings, rod mill sand) were used for cemented filling. In the 1980s, the graded tailings cemented filling was widely used in mines [25], such as the Anqing Copper Mine, Zhangmatun Iron Mine, and Jiaojia Gold Mine. However, it should be noted that fine tailings are harmful to the environment due to the accumulation of fine tailing particles on the surface. Moreover, graded tailings cannot meet the demand of the mine for filling materials.

In 1997, the H-conc cemented filling technology with rod mill sand plus cement was achieved at the Jinchuan Nickel Mine. The slurry concentration of 70wt% was relatively higher than 65wt%; however, this does not indicate a high concentration, but rather that the slurry has the features of not segregating and being able to be transported steadily. In the late 1980s, H-conc whole tailings cemented filling was successfully developed and tested at the Jinchuan Nickel Mine and Fankou Lead-Zinc Mine [26]. The solid content of whole tailings cemented filling can reach 70%–78% after dewatering in the underground backfill field. The process is based on physical/colloid chemistry as the theoretical basis and uses a high-efficiency thickener and vacuum filter to obtain wet tailings. It successfully solves the shortage of filling materials and reduces the impact of pollution on the nearby environment. However, the process is complex, and the cost is high [27]. The German Gronde Lead-Zinc Mine first developed the cemented paste filling technology. The first cemented paste filling system was built at Jinchuan Nickel Mine in 1996 (the landmark stage), and the second cemented paste filling system was constructed at the Tonglushan Copper Mine in 1999. The cemented paste filling method uses dewatering technology, H-conc pumping technology, activation and mixing technology, and computer control technology. Its overall process structure is complex, the filling slurry is free from segregation, the strength of cemented backfill is relatively high, the cement consumption is low, and the paste slurry is highly suitable for long-distance transportation. In 2006, the Huize Lead-Zinc Mine built China's first cemented paste tailings filling; using an introduced deep cone thickener, the filling slurry content can reach 79wt%–81wt% [28]. According to Circular [2014] No. 48 issued by the State Administration of Work Safety, China in 2014, the filling mining method should be the first choice for new underground mines. Moreover, those that cannot use this method should provide demonstrations from design companies or experts, showing that the government attaches great importance to filling mining. Combined with the policies issued by the government in recent years and the emerging filling concepts proposed by scholars at home and abroad, the emerging cemented filling is defined as having typical features, such as green, safe, efficient, intelligent, and low-carbon emission [29–32].

3. Research and preparation of cementitious materials

Cementitious materials are the cementing agents used in filling mining, and traditional Portland cement accounts for 60%–80% of the cost of filling materials. Using potentially active solid wastes can reduce filling cost, which is in line with the green/sustainable progress of mines and has a range of application prospects. The excitation forms include physical/chemical excitations. Fig. 2 shows the excitation principle [33]. Physical excitation is defined as using a mechanical means to grind potentially active solid wastes particles to

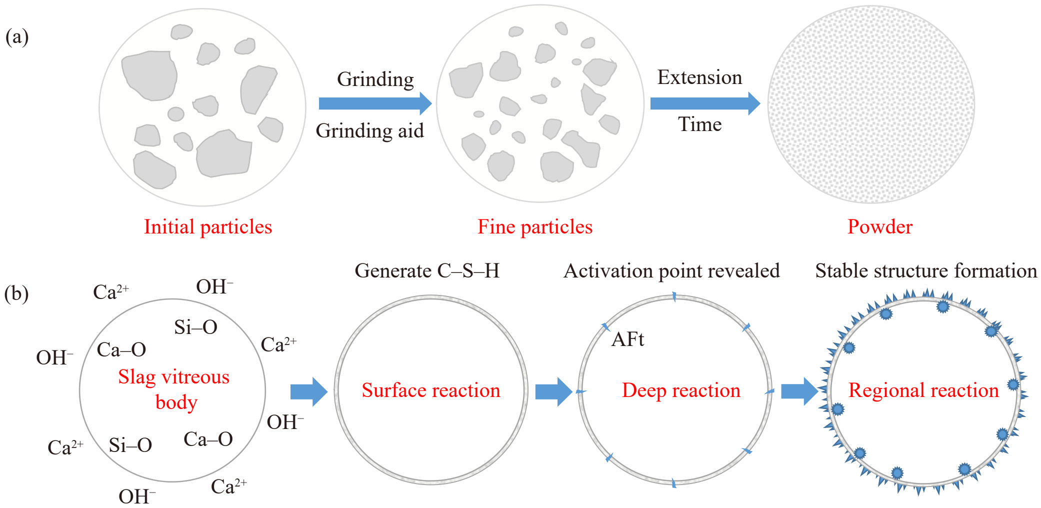

Fig. 2. Illustration of the mechanism of excitation: (a) physical excitation; (b) chemical excitation [33].

a specific fineness (grinding aids include water-reducing agent and triethanolamine). Chemical excitation is performed by adding an alkali/salt substance exciter [34–40].

Xiao [34] used mechanical and chemical means to excite the volcanic ash activity of copper tailings. The results showed that grinding helped the copper tailings to exert physical filling effects. They improved the mechanical properties and activity index of the specimens (Fig. 3). Xiao *et al.* [41] showed that a rise of 10 m^2/kg in the powder's specific surface augmented the strengths of cemented backfill with a cure period of 3, 7, and 28 d by 0.028, 0.057, and 0.122 MPa, respectively. The smaller the fineness of the cemented powder, the more substantial the impact on the strength of early-age specimens. Second, alkaline excitants cover quicklime, sodium hydroxide, water glass, and cement clinker, while salt excitants cover sodium sulfate and desulphurization gypsum. However, numerous scholars mostly use compound excitants to carry out scientific research to expand the features of testing material [42–45]. Zhou *et al.* [39] inspected the impact of various additive combinations on the early quality of whole tailings paste filling materials and their excitation mechanism using scanning electron microscope– energy-dispersive spectroscopy (SEM–EDX) tests. The results specified the effect of composite exciter-intertwined tailings particles, calcium alumina crystals, and gel to build a solid assembly, which improved the strength of the cemented paste backfill at early periods. Li *et al.* [46] found that 0.5wt% sodium sulfate compounded with a 0.2wt% polycarboxylic acid water-reducing agent reduced the cement dosage by 2%, increased the collapse degree by 4.1 cm, and shortened the initial/final set times by 20 min. Using compound excitants can improve the performance of filling slurry simultaneously without increasing the filling cost, and the effect is fast and more suitable for application in the project.

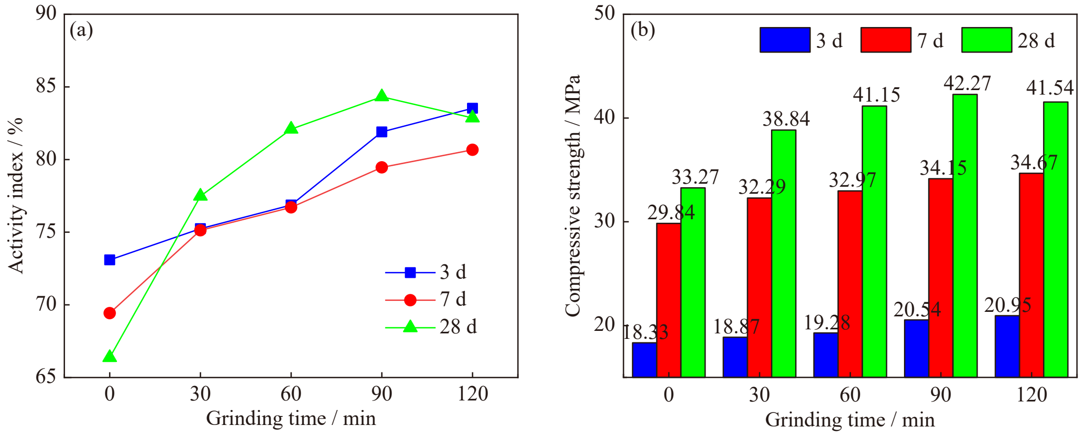

Fig. 3. Copper tailings cementation system at different grinding times: (a) volcanic ash activity index; (b) compressive strength [34].

The blast furnace slag mainly contains CaO, MgO, SiO_2, and Al_2O_3. The superior the glass phase content in the slag, the greater the activity. The larger the specific surface area (particles with a diameter higher than 60 μm are inert, and particles with a diameter lower than 30 μm exhibit a dominant character in the backfill's strength), the better the excitation effect [45]. Under alkaline excitation, the presence of a calcium-rich phase in the internal network structure of the slag vitreous provides a channel for OH^- to enter the vitreous interior from the surface structure, generating stable materials, such as calcium silicate hydrates (CSH) gel, which in turn exhibits good water-hardening activity [47–49]. Zhao [50] used a clinker-free copper slag to substitute the binder as a cementing agent (mixed with MgO), providing theoretical guidance for the safe use of copper slag. Liu *et al.* [51] scrutinized the mechanism of swelling/cementing characteristics of magnesium slag and successfully applied it to the field of mine filling by chemical modification treatment, with a cemented backfill strength of 6.23 MPa at a 28-d curing time. Wang *et al.* [52] used a little smelting water ground nickel slag (with a preferred mass ratio of 85%) as the primary raw material, desulfurization gypsum and calcium carbide slag as the primary activator, and Na_2SO_4 and cement clinker as the additional activator to prepare mining paste backfill composites and studied their hydration mechanism. The quality and activity of blast furnace slag can be assessed according to *Granulated Blast Furnace Slag Used for Cement Production* (GB/T 203-2008). The use of blast furnace slag can provide practical economic and social benefits to mines due to its wide source and low cost.

Fly ash (FA) is grayish-brown, and its activity is determined by its fineness and the dosage of aluminosilicate vitreous humor. The dosage of SiO_2, Al_2O_3, and Fe_2O_3 in FA is 45wt%–60wt%, 20wt%–30wt%, and 5wt%–10wt%, respectively. The following are known according to a large number of experimental research results of domestic and foreign scholars [53–59]. (1) FA has a "micoaggregate" effect in cemented backfill, optimizes the structure of the backfill together with tailings and other materials, reduces the cost of filling, and has good economic/social benefits. (2) Accumulating FA additive is not favorable to the early mechanical strength of cemented backfill, and it has a "slow setting" effect but less influence on the strength of long-term cured filling specimen. (3) Adding FA can greatly increase the flowability of the filling slurry, reduce the pipeline conveying resistance, and improve the pumping performance.

Desulfurization ash slag is a by-product of the dry or semidry desulfurization process and is light gray with a powdered cement-like appearance. Calcium sulfide and FA (f-CaO) have unstable chemistry and hydration characteristics, affecting the wide application of desulfurization ash [60]. Yang *et al*. [40] developed a filling cementitious material for coarse aggregates of rod mill sand (18wt% of desulfurization ash), and the strength of cemented backfill reached 1.57, 3.64, and 7.12 MPa at 3, 7, and 28 d, respectively. Some researchers [61–63] showed that the strength of the aluminate cement compounding system negatively correlated with the amount of desulfurized ash, and the expansion rate was completely linked with the amount of ash. When the amount of desulfurized ash was ≥10wt%, desulfurized ash had a slow setting effect. Typical industrial by-product gypsum contains desulphurization gypsum, phosphogypsum, and hemihydrate gypsum. Desulfurization gypsum exists as individual crystalline particles of a relatively uniform size, with a relatively fast hydration rate and slow volume expansion rate after hardening [64], so the industrial application has achieved a good promotion effect. Phosphogypsum is a by-product emitted from the production of phosphate compost and phosphoric acid, producing approximately 5 t of phosphogypsum per ton of phosphoric acid [65]. Presently, the external policy environment has formed a push-back mechanism for the resource use of phosphogypsum as a waste material, so the resource use and green progress of phosphogypsum cannot be delayed. Rong *et al*. [66] used hemihydrate phosphogypsum (dosed at 427 kg/t) to replace cement as a cementitious material, and the 3-d cured strength reached 2.5 MPa. Moreover, industrial application tests were conducted in a phosphate mine. As shown in Fig. 4, the final setting time was augmented with the increase of desulfurization ash dosage, and the final setting time of the compounding system was extended to 135 min when the dosage was 25wt%. The hemihydrate phosphogypsum filling material prepared under activated conditions exhibited fast early consolidation (average 3-d cured strength of 2.52 MPa), good flow properties (collapse degree > 26 cm), and low water secretion rate, which helped in the filling engineering practice. Although desulfurization gypsum and hemihydrate gypsum have gained good applications in filling mining, the composite gelling material system of phosphogypsum has a complex composition and low early strength, and it contains polluting components, which have not been effectively treated and widely applied. Therefore, raw material selection and cost control are particularly important in preparing phosphogypsum-based gelling materials.

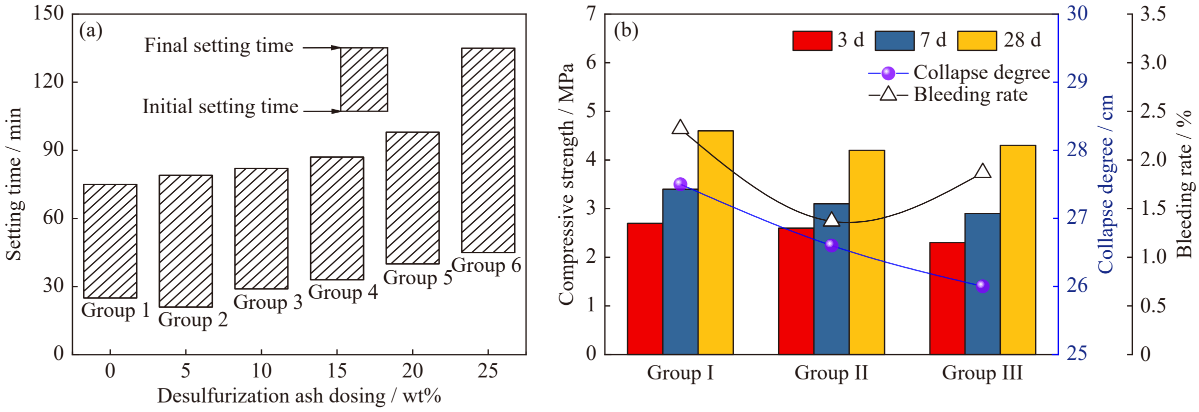

Fig. 4. Performance test results of filling materials: (a) setting time for different desulfurization ash admixtures [59]; (b) strength of tailings–hemihydrate gypsum [66].

Red mud is an industrial waste from bauxite refining, characterized by a high content of fine particles with a large specific surface area [67], and is present as admixtures to other active composites. Studies have shown that red mud helps to improve the workability of the filling material and increase the stability/water retention of the slurry [68–69]. When the red mud/FA mass ratio is 3:2, the binder admixture is 5wt%, which improves the durability of cemented backfill while reducing its permeability [70], providing an awareness of the large-scale utilization of industrial solid waste.

In summary, blast furnace slag, desulphurization ash, red mud, gypsum, and FA are all typical bulk industrial solid wastes. According to the filling characteristics and solid waste excitation principles, the utilization of industrial solid waste to develop and make cemented filling products could not only diminish the backfill costs but also alleviate the environmental contamination problems triggered by the presence of industrial waste. Hence, developing whole solid waste-based cementitious filling materials using industrial waste as the main raw product is proposed. Fig. 5 shows the conceptual framework. It can be interpreted that the development of cementitious filling materials for solid waste starts with field research in metal mines, collecting available industrial waste, and conducting performance tests and theoretical analysis. A series of physical or chemical excitation tests are conducted to select the type of exciter and the dosing amount and to design a reasonable excitation process. Finally, a cementitious material for backfill is prepared that meets the requirements of the mine’s safety, low cost, low-carbon emis-

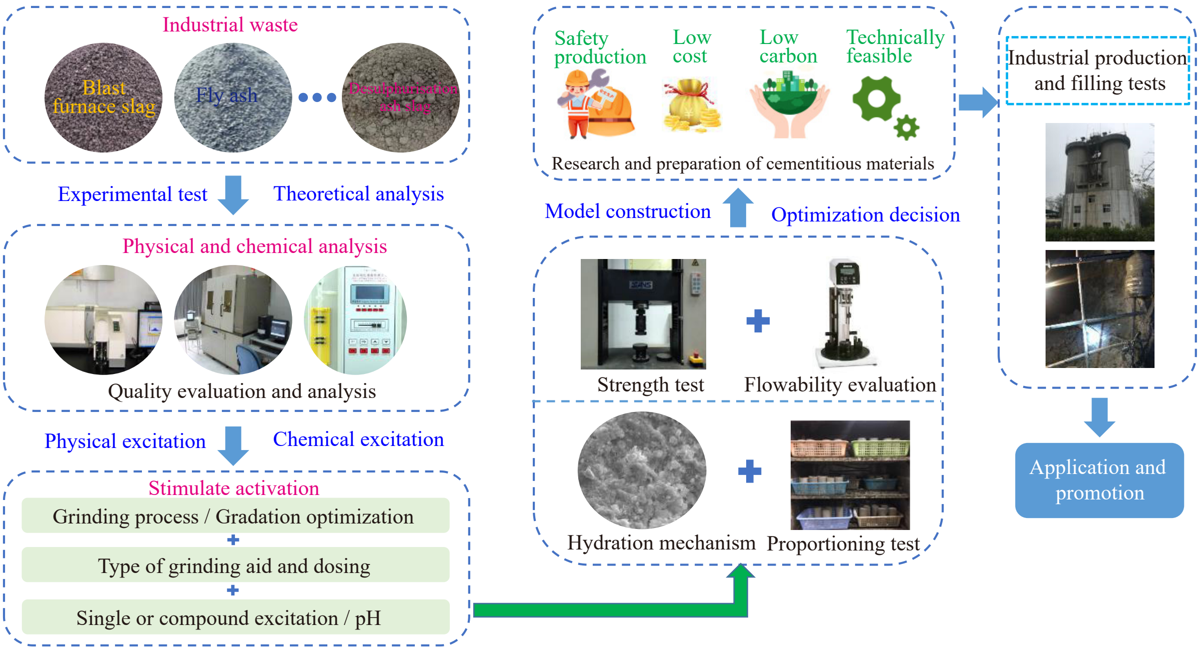

Fig. 5. Conceptual framework for solid waste research and development of cementitious materials.

sion, and technical feasibility. Besides, the relevant industrial application and in-depth promotion will be carried out after the industrial production and filling test is passed.

4. Mechanical properties of cemented backfill

4.1. Static mechanics

Indoor experiments can directly obtain the strength behavior of cemented backfill and its parameters using orthodox loading means, such as uniaxial compression, triaxial compression, shear, and tensile tests. Experimental works were conducted on creep features, loading and unloading, stress percolation, and temperature–stress coupling of cemented backfill. Tang *et al*. [71] used uniaxial compression tests and PFC granular flow software to analyze the strength/crack evolution of layered cemented tailings backfill. Some researchers [72–73] explored the strength of gangue gypsum through uniaxial compression, splitting tensile, shear, and other tests and established a strength prediction model. Guo *et al*. [74] used five-step load routes to replicate various load procedures for working face roofs and established a nonlinear creep basic model with strain rate triggers. The results can offer a basis for the strategy of hydraulic support's advance distance and advance period as well as the reinforcement of the filling column. Wang *et al*. [75] studied the stability features of cemented backfill subjected to triaxial cyclic unloading situations and found that the backfill's damage style is mostly characterized by conjugating shear damage in the upper layer and tensile damage in the cross-layer plane. Fig. 6 shows the synergistic effects of heat transfer, seepage, compression, and hydration that occur during filling to consolidation. The hydration process of cementitious materials is a chemical reaction that releases heat, regulates the change in water pressure between pores by consuming water between filling material substrates, and bears the ground stress with the surrounding rock. Thus, it can be observed that the multi-field effect of the quarry environment has an important influence on the consolidation strength of cemented backfill. Wu *et al*. [76] predicted and analyzed the mechanical properties of the retaining wall through numerical modeling to scrutinize the influence of coupled heat flow, stress, and chemical effects of paste backfill. For the damage features of crack-covering backfill under coupled heat force effects, Hou *et al*. [77] proposed four diverse damage concepts, namely, macroscopic fracture damage, mesoscopic loading damage, mesoscopic thermal damage, and total damage.

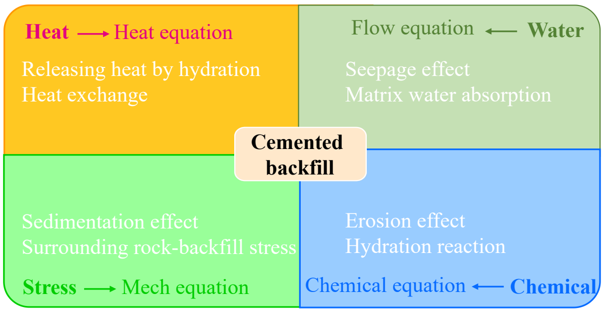

Fig. 6. Schematic representation of the synergistic multi-field effects of cemented backfill [22,76–77].

4.2. Dynamic mechanics

Blasting loads and mining disturbance influence the real stress state of cemented backfill. Numerous researchers have studied the dynamic behavior of cemented backfill in three forms: diverse loading rates, drop weight impact, and split Hopkinson pressure bar (SHPB) testing system. Song *et al*. [78] explored the compression damage features of cemented backfill and its energy dissipation characteristics under five different loading rates by uniaxial compression and found that a critical loading rate phenomenon (showing the effect of strengthening before deterioration) existed for the lower strength of cemented tailings backfill. Yang *et al.* [79] used a WEP-600 test press and JSL-3000 drop weight impact tester to explore the strength features of the Jinchuan cemented backfill with nickel slag under dynamic/static loading. They found that the shear strength of cemented backfill is directed by its friction angle/cohesion, and the relative shear/displacement damage between particles under external loading is dominant. Song *et al.* [80] used the SHPB testing system to analyze the dynamic mechanical features of cemented backfill with diverse levels of alkalized rice straw under single and impact loads and found that alkalized rice straw improved the stability/impact resistance of cemented backfill. It can be observed that the research on dynamic mechanical properties of cemented backfill is gradually gaining attention, and the SHPB test system has significant advantages over the drop weight impact and other methods, which can obtain dynamic mechanical parameters under a high strain rate.

In 1949, Kolsky [81] laid the foundation of the split Hopkinson test system. In 2008, Li *et al.* at Central South University developed a combined dynamic–static SHPB test system [82]. In 2009, Zhao *et al.* at Monash University proposed the true three-axis SHPB test system [83]. In 2020, He *et al.* developed a heat–water–force coupled SHPB test system, which can simultaneously achieve loading axial pressure and circumferential pressure of 0–60 MPa, permeate water stress of 0–45 MPa, and heat of −100°C to +100°C [84]. The international society for rock mechanics and engineering (ISRM) recommended using a 0.5–1 cylinder for the dynamic compression test to improve test accuracy [85]. In addition, Hu *et al.* [86] numerically studied the coupled body at the backfill–rock interface and analyzed the mechanical effects of blast impact on the structure of the coupled body at the interface. Fig. 7 shows the schematic diagram of different dynamic mechanical test principles.

The following were found according to the results of dynamic impact mechanics tests on cemented backfill [88–94]. (1) In general, the dynamic features of cemented backfill are larger than quasi-static ones, and this phenomenon is called the strain rate impact. In conventional tests, when the strain rate is less than 10^{-3} s^{-1}, the strain rate impact is negligible. When the strain rate is more than 10^{2} s^{-1}, it belongs to a high strain rate category. Presently, the strain rate in impact testing of cemented tailings backfill has been as high as 300 s^{-1}. The general test range is mostly below 10^{2} s^{-1}, with a strain rate below 50 s^{-1} at cyclic impact. (2) Cemented tailings backfill dampens the elastic shock wave, and its transmitted wave amplitude is much smaller than the incoming reflected wave. (3) Under dynamic loading, cemented tailings backfill has a high load-bearing capacity, following the law of strain rate impact (Fig. 8). (4) The mean strain rate of perilous instability of common cemented tailings backfill is about 50 s^{-1}, which is a strain rate-sensitive material. Under the action of diverse impact rates, the damage mode of cemented tailings backfill is primarily manifested as instability under the action of tension. (5) Under the same impact velocity, the greater the cement/sand ratio, the higher the strength of cemented backfill. As the cement/sand ratio is identical, the greater the impact rate, the greater the dynamic strength value of cemented tailings backfill. (6) There is a compaction and destruction process of 1–2 times in cemented tailings backfill. The impact number, the setting of nearby pressure, and the addition of fiber reinforcement all subsidize to better escalate the dynamic strength of cemented tailings backfill.

4.3. Factors influencing mechanical properties

A cemented backfill is a nonhomogeneous material made by mixing aggregates, cementitious materials, and water in proportion to each other. The factors that influence its strength and performance include the cement/sand ratio, slurry concentration, aggregate gradation, cementitious materials, curing time, curing conditions, water, and control of the filling system. Normally, the mechanical strength of a cemented backfill rises with a growing cement/sand rate, slurry

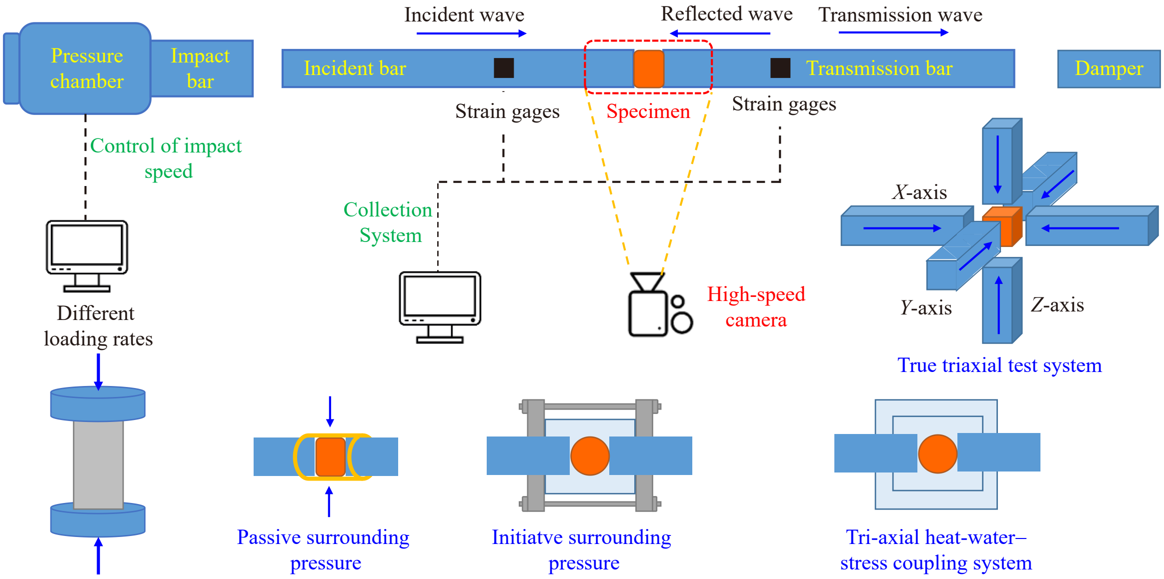

Fig. 7. Schematic diagram of the principles of different dynamic mechanical tests [81–87].

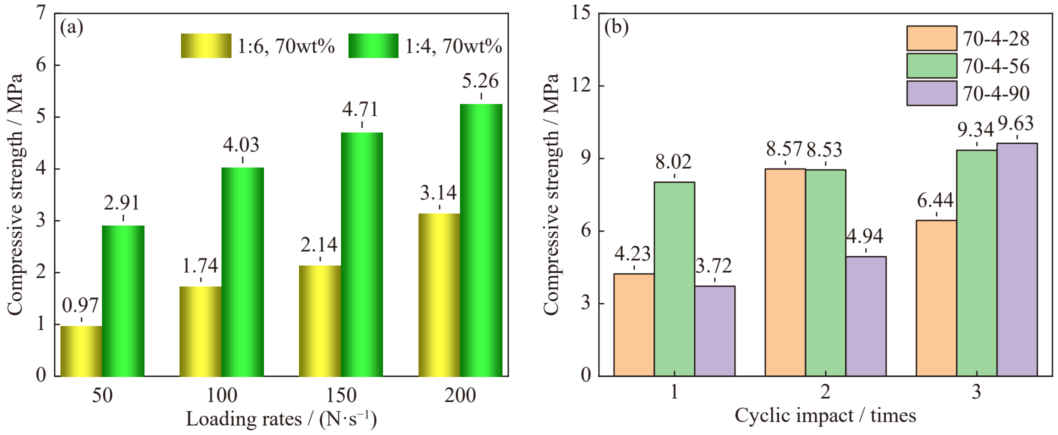

Fig. 8. Strength features of cemented tailings backfill: (a) loading rates; (b) cyclic impacts [90].

concentration, and curing time. This also indicates an increase in filling costs and a longer recovery period. As the main filling component (80% of the total volume), aggregate has a key impact on the stability/durability of cemented backfill. A high proportion of fine-grained aggregate is not favorable to the improvement in the strength of the cemented backfill material [95–96]. The chemistry and pH of pore water in the filling slurry affect the creation of cement hydration materials, with acidic water more likely to erode cemented tailings backfill specimens [97–99]. Jiang *et al.* [100] found that the strength features of sulfur-containing cemented backfill material reveal a trend of growing and then falling with curing time (47.5% at 90 d), and the strength of sulfur-free cemented backfill increased with curing time and then leveled off. Du *et al.* [101] inferred that the erosion of the chlorine salt solution and the changing trend of compressive strength of cemented backfill experienced a growth period, decline period, and stabilization period.

Filling system control is key to filling production. The reliable operation of the system and the stability of the slurry concentration are significant to guarantee the smooth transport and successful application/quality performance of filling. The preparation process and the number of additives affect the characteristics and quality of cementitious materials, and a reasonable selection of cemented products is essential to meet the strength requirements of cemented backfill [102]. At the same time, considering that the actual maintenance conditions in underground hard rock mine sites are significantly different from those in indoor laboratories, the curing temperature, humidity, and external loads have a certain influence on the formation and growth of the strength features of cemented tailings backfill [103–104]. As shown in Fig. 9(a), the field strength of cemented tailings backfill is higher than its laboratory strength, and the filling depth at this time is greater than 300 m [105]. As shown in Fig. 9(b), the field mechanical strength value of cemented backfill is lesser than its laboratory strength, and the filling depth at this time is less than 100 m [106]. Additionally, the mechanical strength design of cemented backfill varies slightly according to the different requirements for the mechanical strength value of cemented backfill during recycling, but usually, higher strength values are used in China than abroad [107].

4.4. Multi-scale mechanics

According to the research method and the feature size, the study of the strength features of cemented backfill can be divided into three levels: macroscopic, mesoscopic, and microscale [108–112]. Typically, the microscopic scale range is <10 μm, the mesoscopic scale ranges from 10 to 1000 μm, and the macroscopic scale range is >1000 μm (Fig. 10). The

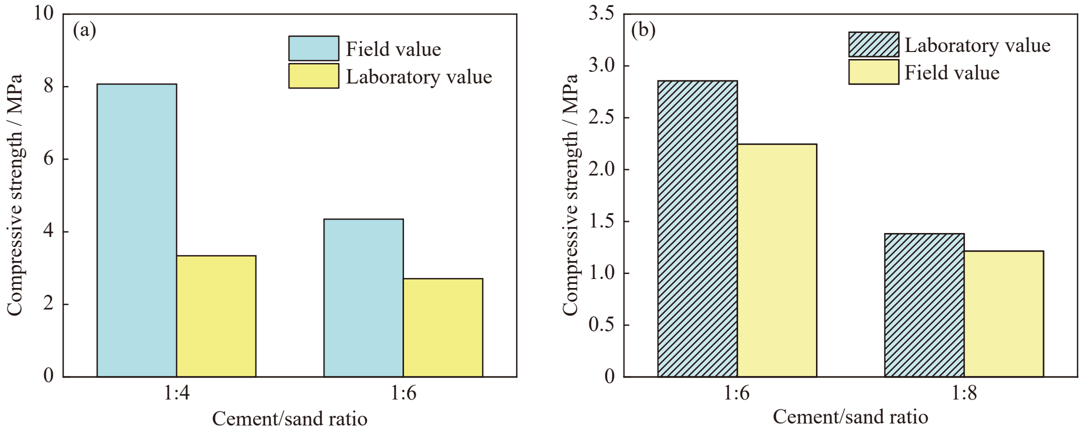

Fig. 9. Compressive strength of laboratory and field cemented backfill: (a) filling depth > 300 m; (b) filling depth < 100 m [105–106].

macroscopic mechanical behavior belongs to the scale range visible to the naked eye. When subjected to external loading, the macroscopic deformation of cemented backfill is achieved by adjusting the internal microstructural parameters. The multi-scale and size effect are two diverse concepts. The former refers to several different study dimensions, while the latter refers to the mechanical properties presented for many different sample sizes. Zhao *et al*. [113] used electronic universal test machine, acoustic emission, scanning electron microscopy, and digital image correlation (DIC) techniques to explore the multi-scale evolution of a cemented backfill under single-bearing load from the emergence, expansion, and penetration of micro-cracks to the generation of macroscopic cracks. Zhao *et al*. [114] prepared the five sets of prismatic specimens with diverse aspect ratios (0.5, 1, 2, 3, and 4) for uniaxial compression tests and explored the damage features of gangue cemented backfill with diverse aspect rates. Song *et al*. [115] performed mechanical tests on various sizes of cemented backfill and combined them with the ABAQUS finite element software to compare and analyze the stability of the excavation process of the stope under the roof of the backfill body with different sizes.

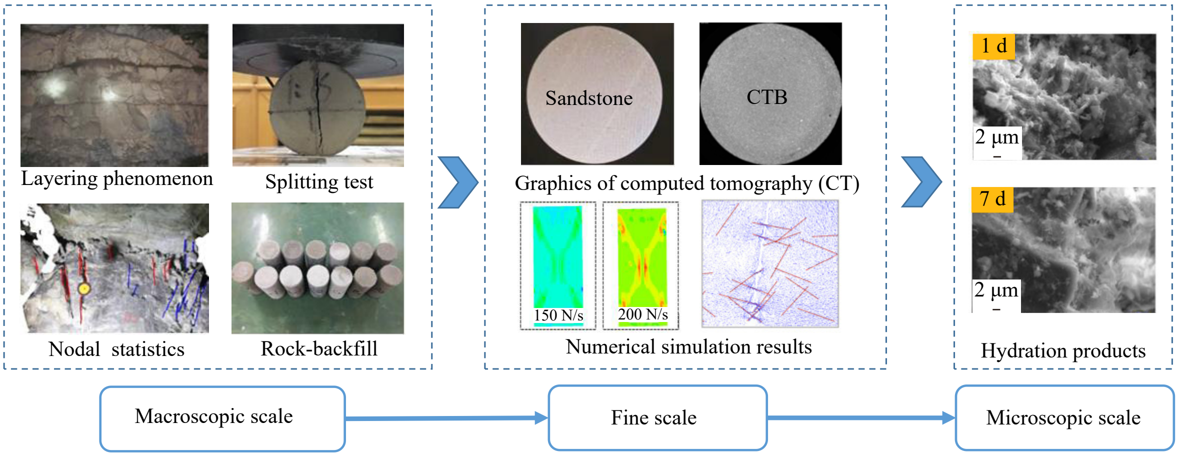

Fig. 10. Research scaling into the physical behavior and performance of cemented backfill [108–115].

X-ray scanning, acoustic emission, and nuclear magnetic resonance techniques are the three common methods used to study the fine structure of geotechnical testing materials [116–120]. As a noninvasive and nondestructive imaging technique, CT scanning has long been used to examine the internal structure of materials. Image analysis software allows the conversion of CT scan results into numerical models or three-dimensional (3D) images for more quantitative and visual analysis of the internal structure of cemented backfill. Yi *et al*. [121] used an *in situ* CT scan to investigate the fracture evolution of tailings colloidal backfill. Belibi Tana *et al*. [122] used digital imaging technology to quantify the pore characteristics of the backfill material to study the link between the microstructure and strength of cemented backfill. Zou *et al*. [123] used computer imaging methods to obtain the pore behavior of mixed aerated-filled concrete and then analyzed the impact of pore structures on the strength features and frost resistance of aerated-filled concrete. It is also challenging to capture the interior structural progress of cemented backfill in real-time during the process of external loading; therefore, numerical modeling is vital to revealing its damage rupture mechanism. Du *et al*. [124] used FLAC^{3D} software to mimic the damage and destruction of gas-bearing coal and rock assemblages below triaxial compression and unloading circumferential pressure by reconstructing the 3D fine structure of the coal–rock assemblage and analyzed its damage and destruction characteristics and energy evolution law. Wei *et al*. [125] used the COMSOL software to perform the numerical simulations of the fluid–solid coupling process under diverse stress conditions and explored the water pressure mechanism on the rock damage process. The common testing methods at the microscopic scale include SEM, X-ray diffraction (XRD), and X-ray fluorescence (XRF) [126–127]. Researchers [128–129] found that calcium vanadinite and CSH gels were produced within cementitious materials after hydration, which contributed to its consolidation and hardening by XRD and SEM. Loykaew and Utara [130] explored the microstructural mechanism of the interface between rubber particles and hydration products under diverse maintenance ages and acidic conditions. Xu *et al*. [131] found that the morphology and size of calcium vanadinite and CSH gels within cemented backfill specimens varied at different cure times.

In summary, the methods for investigating the mechanical features of cemented backfill include basic mechanical tests, numerical simulations, and theoretical analyses. As shown in Fig. 11, the results of the basic strength tests are presented in a multi-scale and multidimensional manner depending on the test methods. Simultaneously, strength tests provide the necessary mechanical parameters for numerical simulations and have an internal relationship with the numerical simulations. Fundamental theoretical analysis and basic mechanical tests govern excellent test approaches. For example, high-speed cameras, Fourier transform infrared spectrometer (FTIR), DIC technology, and acoustic emission can assist the mechanical tests in obtaining more valuable data and conducting comprehensive multi-scale and multidimensional analyses.

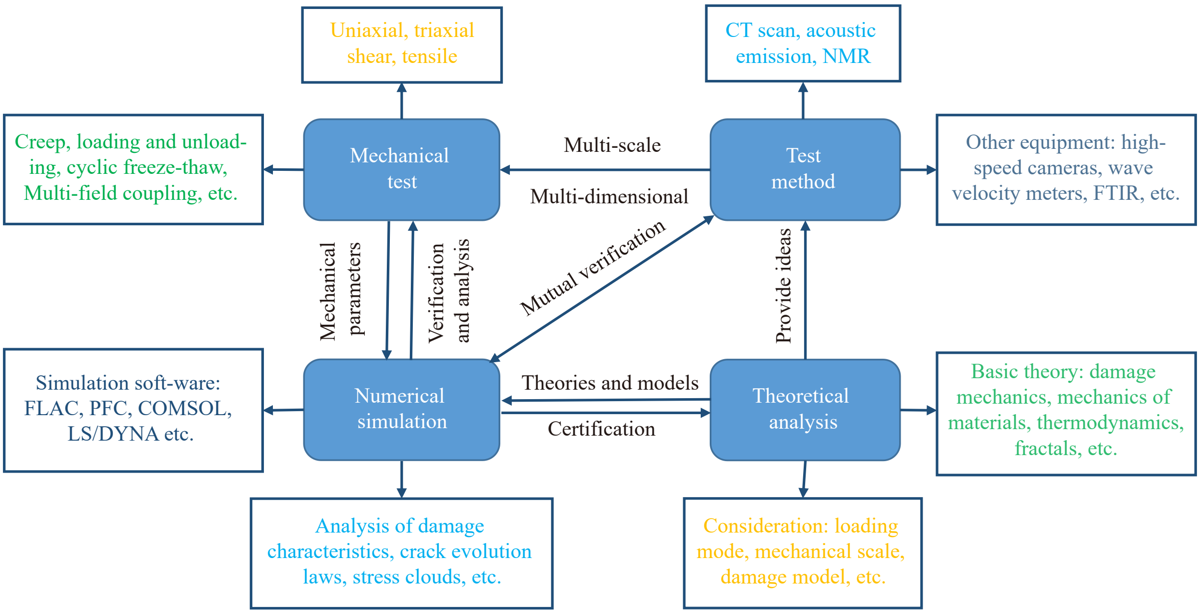

Fig. 11. Framework of research ideas on the mechanical properties of cemented backfill.

5. Flow features of the filling slurry

5.1. Working characteristics

The working features of the filling slurry are evaluated in terms of collapse, diffusion, consistency, segregation, bleeding rate, and shrinkage (Fig. 12). The collapse, diffusion, and consistency properties reflect the flowability of the filling slurry, the delamination and bleeding rate reflect the stability of the filling slurry, and the shrinkage rate represents the denseness of the filling slurry. The degree of collapse is defined as the change between the final height of the filling slurry collapsing under its weight and the top of the collapsed cylinder (the indicator for whole tailings paste filling slurry is 180–260 mm [132]), and the index of diffusion is the average of the plane dimensions of the filling slurry. In general, the larger the index of collapse and diffusion, the better the flowability of the filling slurry. The consistency is measured using a mortar consistency meter, which evaluates the feasibility of piping the filling slurry. The segregation is the difference between the filling slurry before and after resting using a mortar consistency meter (the second time the lower mortar after resting is taken from the segregation cylinder) and is a central index to evaluate the step of filling delamination. The bleeding rate is the percentage by mass of water precipitated in the filling slurry compared to the total water used, with an indicator of 1.5%–5% for whole tailings paste filling slurry [132]. The shrinkage rate [133] is the percentage of shrinkage of the volume of filling slurry before and after solidification or before and after demolding (others can use the line shrinkage rate, with the gage of total paste tail-

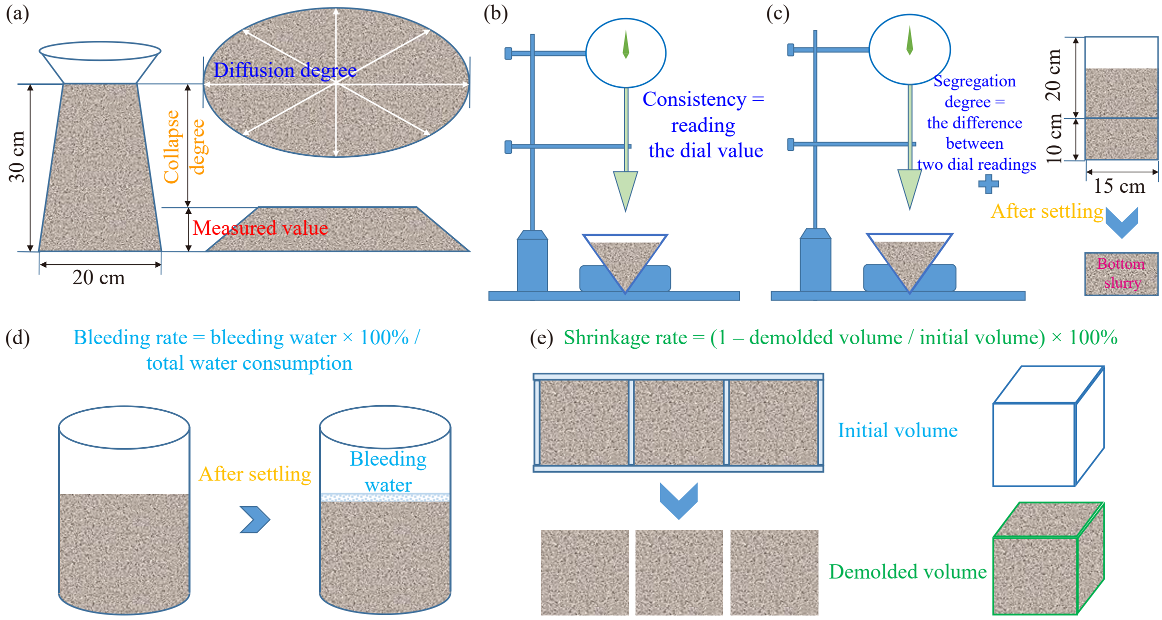

Fig. 12. Filling slurry working performance test: (a) collapse and diffusion degree; (b) consistency; (c) segregation degree; (d) bleeding rate; (e) shrinkage rate.

ings of <5% [132]), indirectly reflecting the topping rate of cemented backfill. That is, the effectiveness of filling affects the stability of the filled quarry area.

5.2. Rheological properties

Filling slurry is self-flowing or pumped through the pipeline to the underground quarry. Therefore, it needs to meet the mine flow performance requirements. The study of the filling slurry's rheology is crucial to technical issues, such as the preparation process, pipeline transport design, and optimization of mine filling. The common testing methods include the rheometer, the L-tube way, and the ring-tube method, depending on the rheological characteristics of the filling slurry. The influencing factors hold the slurry ratio (e.g., solid content, cement/sand ratio, binder admixture, and type), the aggregate ratio (e.g., coarse aggregate waste rock), and the particle size gradation. For the rheological test of coarse aggregate blended slurries, the stability of the data results obtained using a rheometer was not effective, and problems were noted with the distortion of the slurry rheological parameters [134]. Moreover, the viscosity coefficient and yield stress of the filling slurry gradually increased with growing fines grade admixture [135]. According to "GB/T 39489-2020: Technical specification for the total tailing paste backfill," the coarse aggregate and the fine aggregate particle sizes range from 4.75 to 20 mm and 0.075 to 4.75 mm, respectively, and the yield stress of the whole tailings paste backfill ranges from 100 to 200 MPa.

With the ongoing development of fluid mechanics, many scholars have developed various rheological models to characterize the quantitative link between a slurry's shear stress and shear rate [136–138]. Among them, the viscosity coefficient (not constant and is measured in Pa·s), yield stress (the nature of the resistance to the cohesion of the slurry when the slurry shifts from a stationary to a moving state), and flow index (the Newtonian body flow index is 1) are important indicators to evaluate the slurry's rheology. As cemented paste fillings, considered as non-Newtonian fluids, usually maintains a relatively stable and homogeneous flow during transport. Yin *et al.* [139] also inspected the impacts of temperature, tailings/aggregate rate, and healing time on the slurry's rheology and showed that the shear stress was adversely linked with temperature and undoubtedly connected with the value of the tailings/aggregate ratio and healing time. Considering the high cost of rheometers and the limits of their use in mines, Wu *et al.* [140] proposed and compared an analytical and empirical model to characterize the rheological properties based on the degree of expansion. Liu *et al.* [141] developed an experimental system for vertical tube slurry conveying based on electrical resistance tomography based on the flow behavior characteristics of vertical tube self-flow conveying of paste slurry. Lan and Wu [142] experimentally derived the flow equation for the pipe layer based on the Herschel–Bulkley model and found that the solved parameters were in harmony with the outcomes gained from rheometer tests. Researchers [143] conducted an industrial-scale annular tube transport test of coarse aggregate paste transport features and analyzed the difference between rheometer test results and annular tube test consequences. It can be interpreted that most of the methods and devices for measuring the rheological parameters of the slurry have certain limitations and need to be selected appropriately.

6. Prospects in filling mining

The transformation of filling mining technology has a profound impact on metal mines, and the emerging cemented filling has effectively solved many mining challenges since it is "green, safe, efficient, intelligent, and low-carbon." The concept of new-age filling gradually gains popularity and leads the way in transforming the sustainable development of mines.

6.1. Green mining and low-carbon filling

In 2007, the China International Mining Conference first proposed "green mining." In 2017, the report of the 19th National Congress of the Communist Party of China made the vital deployment of "promoting green development." In 2018, the Ministry of Natural Resources, People's Republic of China issued green mine construction standards for nine industries, including nonferrous metals. In 2019 and 2020, more than 1100 national green mines were constructed in China. The green mining model follows the three basic principles of "sustainable profitability, circular economy, and geo-mining harmony" [144] and prioritizes ecological protection. Resource-saving and environment-friendly mineral development technologies are developed, and the environmental problems associated with mining and extraction waste are resolved [5]. Green mining reflects the economic, environmental, and social benefits of mines by combining resource reuse, waste rock and tailings backfilling, open space utilization, and greening of pits [145].

The filling mining technology is an effective means to help achieve a 15% carbon reduction in 5 years based on the urgent need for low-carbon development in the mining industry under "the carbon peaking and carbon neutrality goals" [146]. Chen *et al.* [147] explored the carbon absorption capacity and mechanical properties of cemented backfill at a CO_2 dosage of 1.5%, aiming to contribute to carbon emission reduction and promote the environmentally friendly development of the mining industry. Su *et al.* [148] developed a technology to prepare FA-based matrix foams suitable for mine filling by covering a foaming admixture. Qiu *et al.* [149] prepared a low-carbon cemented material alkali-excited slag for cemented paste filling.

The mining industry is associated with environmental pollution and ecological damage and is a typical representative of high energy consumption and carbon emissions. Filling mining belongs to the category of green mining and should follow the principle of "localization" and adopt the modes of waste-free mining and resource utilization to help achieve "earth–mine harmony." Meanwhile, low-carbon resource development is the inevitable trend of mining development, and the future is full of opportunities and challenges. Among them, energy consumption control during mining, high-value comprehensive utilization of bulk solid waste, and carbon sequestration and utilization are the main aspects of low-carbon emission reduction in filling mining.

6.2. Smart mining/filling

In 2016, the *Five-Year National Plan on Mineral Resources (2016–2020), China*, proposed to briskly promote scientific and technological innovation in the mining industry and accelerate the construction of digital, intelligent, informative, and automated mines [150]. In 2018, the *General Technical Specification for Smart Mine Information Systems* (GB/T 34679-2017) formally included mine intelligence in the national standard. The 2020 conference on “5G + industrial internet” in the mining industry pointed out that the construction of 5G infrastructure should continue to be strengthened to create safe and efficient smart mines [151–152]. Thus, it can be observed that smart mines are a positive trend in the future growth of mines. On the one hand, national policies continue to support the modernization of the traditional mining sector with high technology, such as digital technology, driverless technology, and 5G information technology. On the other hand, mine intelligence helps to reduce labor intensity, improve production efficiency, and ensure production safety [153].

China has gradually built up mining enterprises with typical intelligent features. (1) Some enterprises are represented by intelligent and unmanned equipment. The Xitieshan Lead-Zinc Mine has achieved unmanned tracked equipment. The Fankou Lead-Zinc Mine has intelligent mining equipment and achieves a mechanized unmanned mining rate of 83%. The Dongguashan Copper Mine has unmanned motor trucks and has achieved remote control processes. (2) Some enterprises are represented by intelligent systems and integrated control. The Pulang Copper Mine is one of the first Chinese metal mines with an intelligent system. The Xingshan Iron Mine has achieved the goals of information digitization, equipment modernization, and production visualization. (3) Some enterprises are represented by 5G technology, such as the “5G + artificial intelligence” remote control of rock drilling dollies at the Sanshandao Gold Mine. The Laixi Gold Mine used “5G + VR/AR” technology to achieve network coverage of underground tunnels. The Nannihu Molybdenum Mine employed the “dual 5G” technology in the production and management of an open-pit mine.

Domestic scholars and researchers have also made great contributions to filling mining automation and intelligence. Qi *et al*. [31] analyzed the research progress of the new generation of artificial intelligence in flocculation and settlement, filling proportioning, and pipeline transportation and proposed the concept of “intelligent filling system.” Wang *et al.* [154] took the mining filling of the Shandong Gold Group as an example and found that the combination of “artificial intelligence technology,” “intelligent filling system,” and “filling data platform” could achieve a dynamic adjustment of filling process parameters and system fault diagnosis. Chen *et al.* [155] designed a “cloud, edge, and end” smart control architecture for filling systems, enabling the intelligent operation of production during whole tailings filling in the Wushan Copper Mine. Besides, data processing is performed through methods such as industrial neural networks and decision trees. Intelligent models are established to predict the backfill strength and slurry composition. Moreover, intelligent monitoring equipment is installed to achieve filling slurry control [156–163]. All of these are important research directions for intelligent mine filling. In summary, based on new technologies, new theories, and high-tech equipment, big data and cloud platforms will be the future development trend of smart filling (Fig. 13). Furthermore, smart filling is important in promoting the filling technology’s application and green construction of mines. However, when filling deep mines, the stability and reliability of the operation of intelligent equipment are affected, restricting the rapid development of China’s mining modernization. Therefore, it is important to increase investment in scientific research and promote the localization of intelligent equipment.

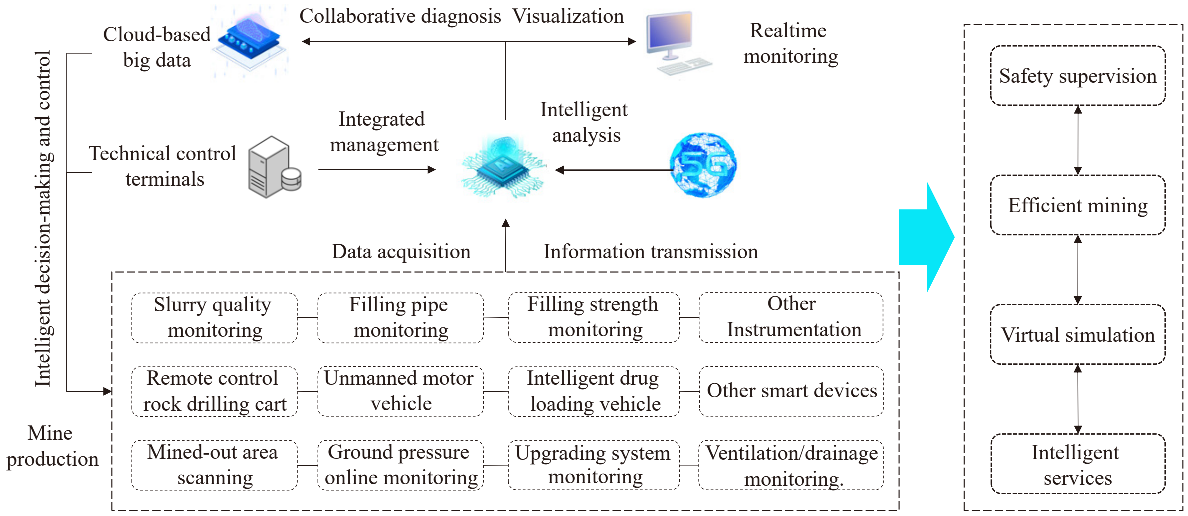

Fig. 13. Smart mine control system composition [156–163].

6.3. Deep mining/filling change philosophy

The development and use of deep ores agree with the strategic requirements of the four areas of "deep space/sea/blue/earth" proposed in the *National Medium and Long-Term Science and Technology Development Plan (2006–2020), China*. Affected by the complex environment, deep mines face difficulties such as deteriorated operating environment, increased risk of ground pressure disasters, strong mining disturbance, and increased lifting and transportation costs. Deep high temperatures and high stress are important factors that affect the quality of cemented backfill. Among them, temperature and stress have a relatively facilitating effect on the early curing process of cemented backfill [164–165]. However, the harmful heat generated inside the maintenance temperature is too high, making cemented backfill prone to microfracture [166]. Furthermore, the maximum confining consolidation stress determines the degree of excitation of the strength of cemented backfill, and the load-bearing performance of the coupled mineral rock–backfill structure is closely related to the environmental temperature and the principal stress direction [167]. Nevertheless, the mechanical properties of cemented backfill under the temperature–stress coupling have not yet been clarified. Deep-filling mining is a dynamic process, and the effects of cemented backfill are mainly reflected in regional ground pressure control, improvement in the local stress environment, and absorption of geothermal heat. Hence, it is crucial to reasonably arrange the recovery sequence and isolation of mines, which can effectively reduce the disturbance impact during the recovery process. Presently, the deep-filling quality testing methods include *in situ* sampling and *in situ* transparent monitoring. Materials, such as large deformation anchor rods, are gradually popularized and applied [168–169].

The concept and strategy of changing the unfavorable factors into favorable factors are proposed based on the environment of high stress/temperature/well depth and multiple empty areas in deep mining. (1) Disasters, such as rock bursts, can occur due to factors, including high stresses in the original rock and the emergence of ground pressure during mining or increased mining costs with increasing depth. For underground metal mining, high stress-induced non-blasting continuous mining can improve the efficiency of mining deep hard rocks and reduce the mining costs during blasting [170]. Second, given the contact mechanism between cemented backfill and nearby rock, the essence of "simultaneous filling" is to use cemented backfill to form an adequate support for nearby rock and reduce the disasters caused by untimely filling [30,171–173], offering guidance for the production practice of complex ore bodies in mines. (2) The high-temperature environment reduces production efficiency and restricts production safety. By taking advantage of the high temperatures at depth, solution leaching mining and the synergistic mining of geothermal resources can be used to harvest high-value mineral resources and geothermal heat [174]. Alternatively, functional cooling/cooling storage filling can be used to absorb heat from the nearby rock and achieve cooling in the form of heat conduction, convection, and radiation. Heat exchange or extraction pipelines can be pre-buried during filling [175–176]. (3) High well depth makes lifting difficult; thus, reform strategies, such as mine intelligence, fluidized mining, and filling, are beneficial to achieve waste rock out of the pit and reduce deep lifting and mining costs [177–178]. However, reform strategies, such as fluidized mining, are still in the theoretical conception.

7. Summary

Filling mining has undergone decades of continuous development in China and is now mainly based on cemented filling, achieving filling targets such as high concentration, no segregation, and low cementitious agent consumption, which can be safely transported to the underground.

The development of mining cementitious materials using bulk industrial solid waste is an important future development direction, and material proportioning tests should be conducted on local materials to reduce the cost of mine backfill. The performance stability of cementitious materials is crucial, given the different sources and batches of raw materials. To promote the application of whole solid waste cementitious materials in mines, it is crucial to strengthen the cooperation between mines and universities or other research institutions and to develop the corresponding technical specifications and quality standards.

Combining basic mechanic tests, numerical simulations, and theoretical analyses, multi-scale and multidimensional research can be performed on the mechanical properties of cemented backfill. Exploring the long-term mechanical behavior of cemented backfill under mining disturbance conditions, revealing the mechanism of damage and rupture of cemented backfill under the multi-field coupling effect, developing experimental devices with true 3D stress fields, and optimizing coupled rock–backfill mechanical model are important directions for future research in cemented backfill mechanics. Simultaneously, the study of the rheological features of the filling slurry should be considered.

Based on forward-looking theories and technologies, the construction of high-standard large-scale intelligent mines and the realization of mining of deep resources will help promote China's mines to achieve a comprehensive upgrade in the industrial structure. The future progress direction of mining with backfill includes green mining, low-carbon filling, smart mining/filling, and deep mining transformation. In addition, a future study should focus on the construction of the "industry/academia/research" system and then gradually form the core competitive advantage of China's filling mining.

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Conflict of Interest

Erol Yilmaz is a youth editorial board member for this journal and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

References

[1] S.F. Wang, L.C. Sun, Y. Tang, Y. Jing, X.B. Li, and J.R. Yao, Field application of non-blasting mechanized mining using high-frequency impact hammer in deep hard rock mine, *Trans. Nonferrous Met. Soc. China*, 32(2022), No. 9, p. 3051.

[2] M.F. Cai, D.L. Xue, and F.H. Ren, Current status and development strategy of metal mines, *Chin. J. Eng.*, 41(2019), No. 4, p. 419.

[3] J. Wei, J.J. Zhang, X. Wu, and Z.Y. Song, Governance in mining enterprises: An effective way to promote the intensification of resources—taking coal resources as an example, *Resour. Policy*, 76(2022), art. No. 102623.

[4] J.Y. Peng, S. Zhang, Y.Y. Han, B.T. Bate, H. Ke, and Y.M. Chen, Soil heavy metal pollution of industrial legacies in China and health risk assessment, *Sci. Total Environ.*, 816(2022), art. No. 151632.

[5] X.J. Liu, H.L. Hou, Y.X. Sun, and P. Zhou, Thinking about the connotation and realization path for green mining in China, *Min. Res. Develop.*, 41(2021), No. 10, p. 181.

[6] M.F. Cai, P. Li, W.H. Tan, and F.H. Ren, Key engineering technologies to achieve green, intelligent, and sustainable development of deep metal mines in China, *Engineering*, 7(2021), No. 11, p. 1513.

[7] H.J. Lu, C.C. Qi, Q.S. Chen, D.Q. Gan, Z.L. Xue, and Y.J. Hu, A new procedure for recycling waste tailings as cemented paste backfill to underground stopes and open pits, *J. Cleaner Prod.*, 188(2018), p. 601.

[8] H.F. Qiu, F.S. Zhang, L. Liu, D.Z. Hou, and B.B. Tu, Influencing factors on strength of waste rock tailing cemented backfill, *Geofluids*, 2020(2020), art. No. 8847623.

[9] T.T. Xu, C.Y. Kang, and H. Zhang, China's efforts towards carbon neutrality: does energy-saving and emission-reduction policy mitigate carbon emissions, *J. Environ. Manage.*, 316(2022), art. No. 115286.

[10] L.J. Dong, X.J. Tong, X.B. Li, J. Zhou, S.F. Wang, and B. Liu, Some developments and new insights of environmental problems and deep mining strategy for cleaner production in mines, *J. Cleaner Prod.*, 210(2019), p. 1562.

[11] Y. Wang, C.H. Guo, X.J. Chen, *et al.*, Carbon peak and carbon neutrality in China: goals, implementation path, and prospects, *China Geol.*, 4(2021), No. 4, p. 1.

[12] A.X. Wu, G.Z. Jiang, and Y.M. Wang, Review and development trend of new type filling cementing materials in mines, *Met. Mine*, 3(2018), p. 1.

[13] G.R. Feng, Z.H. Wang, T.Y. Qi, *et al.*, Effect of velocity on flow properties and electrical resistivity of cemented coal gangue-fly ash backfill (CGFB) slurry in the pipeline, *Powder Technol.*, 396(2022), p. 191.

[14] R.F. Yan, S.H. Yin, J.M. Liu, L. Zou, Y.B. Mo, and Y.Y. Kou, Rheological properties and calculation models of coarse aggregate paste with polypropylene fiber, *J. Cent. South Univ. Sci. Technol.*, 53(2022), No. 4, p. 1450.

[15] W. Liang, K. Li, J.S. Luo, Y.L. Zhe, M.T. Xu, and F.S. Feng, Experimental study on the interaction between backfill and surrounding rock in the overhand cut-and-fill method, *Minerals*, 12(2022), No. 8, art. No. 1017.

[16] G.L. Xue and E. Yilmaz, Strength, acoustic, and fractal behavior of fiber reinforced cemented tailings backfill subjected to triaxial compression loads, *Constr. Build. Mater.*, 338(2022), art. No. 127667.

[17] B. Sirait, R.K. Wattimena, and N.P. Widodo, Rockburst prediction of a cut and fill mine by using energy balance and induced stress, *Procedia Earth Planet. Sci.*, 6(2013), p. 426.

[18] J.M. Zhu, Z.W. Ma, J.H. Xu, and J.N. Wu, Research on the technology of filling and repeated mining in thick coal seam affected by small mine gob area, *Procedia Eng.*, 26(2011), p. 1150.

[19] G.D. Lu, X.G. Yang, S.C. Qi, G. Fan, and J.W. Zhou, Coupled chemo-hydro-mechanical effects in one-dimensional accretion of cemented mine fills, *Eng. Geol.*, 267(2020), art. No. 105495.

[20] X.G. Wang and K.Y. Tang, Overview of cut and fill method for mines, *Modern Min*, 12(2008), p. 2.

[21] H. Hu and H.H. Sun, Development of backfill technology and the new backfill process using paste-like material, *China Min. Mag.*, 10(2001), No. 6, p. 47.

[22] L. Liu, Z.Y. Fang, B. Zhang, M. Wang, H.F. Qiu, and X.Y. Zhang, Development history and basic categories of mine backfill technology, *Met. Mine*, 3(2021), p. 10.

[23] X.M. Wang, *A Study of Filling Materials and Pipeline Transportation Systems in Deep Mines* [Dissertation], Central South University, Changsha, 2005, p. 9.

[24] S. Cao, G.L. Xue, E. Yilmaz, and Z.Y. Yin, Assessment of rheological and sedimentation characteristics of fresh cemented tailings backfill slurry, *Int. J. Min. Reclam. Environ.*, 35(2021), No. 5, p. 319.

[25] D.Q. Ding, *Research on the Theory and Technology of Filling the Underground Mining Area with Paste* [Dissertation], Central South University, Changsha, 2007, p. 3.

[26] R.C. Yu, Development and innovation of cemented filling technology in China, *China Min. Eng.*, 39(2010), No. 5, p. 3.

[27] S.H. Yin, Y.J. Shao, A.X. Wu, H.J. Wang, X.H. Liu, and Y. Wang, A systematic review of paste technology in metal mines for cleaner production in China, *J. Cleaner Prod.*, 247(2020), art. No. 119590.

[28] H.Y. Cheng, A.X. Wu, S.C. Wu, *et al.*, Research status and development trend of solid waste backfill in metal mines, *Chin. J. Eng.*, 44(2022), No. 1, p. 13.

[29] C.L. Wang, Z.Z. Ren, Z.K. Huo, *et al.*, Properties and hydration characteristics of mine cemented paste backfill material containing secondary smelting water-granulated nickel slag, *Alex. Eng. J.*, 60(2021), No. 6, p. 4961.

[30] L. Liu, J. Xin, B. Zhang, X.Y. Zhang, M. Wang, H.F. Qiu, and L. Chen, Basic theories and applied exploration of functional backfill in mines, *J. China Coal Soc.*, 43(2018), No. 7, p. 1811.

[31] C.C. Qi, X.Y. Yang, G.C. Li, Q.S. Chen, and Y.T. Sun, Research status and perspectives of the application of artificial intelligence in mine backfilling, *J. China Coal Soc.*, 46(2021), No. 2, p. 688.

[32] J.J. Li, E. Yilmaz, and S. Cao, Influence of industrial solid waste as filling material on mechanical and microstructural characteristics of cementitious backfills, *Constr. Build. Mater.*, 299(2021), art. No. 124288.

[33] J.L. Wu, *Experimental Research on High Calcium CFB Desulfurization Ash as Raw Material and Admixture of Sulphoaluminate Cement* [Dissertation], Zhejiang University, Hangzhou, 2021, p. 6-7.

[34] L.N. Xiao, Effect of mechanical-chemical coupling activation on pozzolanic activity of copper tailings, *Bull. Chin. Ceram. Soc.*, 39(2020), No. 11, p. 3595.

[35] G. Yao, Q. Wang, Y.W. Su, J.X. Wang, J. Qiu, and X.J. Lyu, Mechanical activation as an innovative approach for the preparation of pozzolan from iron ore tailings, *Miner. Eng.*, 145(2020), art. No. 106068.

[36] Q.M. Lu, Z. Wang, R.L. Zhang, and H.Q. Han, Excitation function of chemical admixture on fly ash-slag-cement cementitious system, *Bull. Chin. Ceram. Soc.*, 37(2018), No. 8, p. 2516.

[37] H. Nguyen, E. Adesanya, K. Ohenoja, L. Kriskova, Y. Pontikes, P. Kinnunen, and M. Illikainen, Byproduct-based ettringite binder – A synergy between ladle slag and gypsum, *Constr. Build. Mater.*, 197(2019), p. 143.

[38] Z.Y. Zhao, K.H. Guo, and X.L. Wang, A binder prepared by low-reactivity blast furnace slags for cemented paste backfill: Influence of super-fine fly ash and chemical additives, *Constr. Build. Mater.*, 327(2022), art. No. 126988.

[39] Q. Zhou, J.H. Liu, A.X. Wu, and H.J. Wang, Early-age strength property improvement and stability analysis of unclassified tailing paste backfill materials, *Int. J. Miner. Metall. Mater.*, 27(2020), No. 9, p. 1191.

[40] X.B. Yang, Y.D. Wang, Q. Gao, J.Y. He, and L. Qu, Research on a new cementitious materials based on desulphurization ash and fly ash and its application in Jinchuan Mine, *Multipurp. Util. Miner. Resour.*, 4(2019), No. 4, p. 130.

[41] B.L. Xiao, Z.Q. Yang, D.X. Chen, and Q.A. Gao, Impacts of slag-based-binder fineness on strength in mining backfill, *Sci. Sin. Technol.*, 49(2019), No. 4, p. 402.

[42] P. Wu, Q. Wang, Q. Liu, and X.J. Lv, Preparation and hydration characteristics of soda residue-slag based cementitious materials, *J. China Univ. Min. Technol.*, 51(2022), No. 4, p. 802.

[43] J.S. Qiu, K. Cheng, R.Y. Zhang, Y. Gao, and X. Guan, Study on the influence mechanism of activated coal gangue powder on the properties of filling body, *Constr. Build. Mater.*, 345(2022), art. No. 128071.

[44] T. Yılmaz, B. Ercikdi, and F. Cihangir, Evaluation of the neutralization performances of the industrial waste products (IWPs) in sulphide-rich environment of cemented paste backfill, *J. Environ. Manage.*, 258(2020), art. No. 110037.

[45] L. Dong, Q. Gao, S.Q. Nan, and J.Q. Du, Performance and hydration mechanism of new super fine cemented whole-tailings backfilling materials, *J. Cent. South Univ. Sci. Technol.*, 44(2013), No. 4, p. 1573.

[46] H. Li and H.J. Wang, Influence law of compound admixture on the mechanical properties of filling slurry before and after curing, *Acta Mater. Compos. Sin.*, 39(2022), No. 8, p. 3940.

[47] Y. Li, H.H. Sun, Y.H. Zhao, and N. Wang, Research of formation mechanism on cementitious reactivity of water-cooled slag, *Chin. J. Proc. Eng.*, 7(2007), No. 1, p. 79.

[48] G. Xie, Y.L. Suo, L. Liu, *et al.*, Mechanical grinding activation of modified magnesium slag and its use as backfilling cementitious material, *Case Stud. Constr. Mater.*, 18(2023), art. No. e01778.

[49] B.S. Gebregziabiher, R. Thomas, and S. Peethamparan, Very early-age reaction kinetics and microstructural development in alkali-activated slag, *Cem. Concr. Compos.*, 55(2015), p. 91.

[50] D.F. Zhao, Reactive MgO-modified slag-based binders for cemented paste backfill and potential heavy-metal leaching behavior, *Constr. Build. Mater.*, 298(2021), art. No. 123894.

[51] L. Liu, S.S. Ruan, Z.Y. Fang, D.Z. Hou, B. Zhang, and W.J. Sun, Modification of magnesium slag and its application in the field of mine filling, *J. China Coal Soc.*, 46(2021), No. 12, p. 3833.

[52] F. Wang, Q.Q. Zheng, G.Q. Zhang, C.L. Wang, F. Cheng, and G. Lin, Preparation and hydration mechanism of mine cemented paste backfill material for secondary smelting water-granulated nickel slag, *J. New Mater. Electrochem. Syst.*, 23(2020), No. 1, p. 52.

[53] T.Y. Qi, G.R. Feng, Y.J. Zhang, J. Guo, and Y.X. Guo, Effects of fly ash content on properties of cement paste backfilling, *J. Residuals Sci. Technol.*, 12(2015), No. 3, p. 133.

[54] Y. Zhao, A. Taheri, M. Karakus, Z.W. Chen, and A. Deng, Effects of water content, water type and temperature on the rheological behaviour of slag-cement and fly ash-cement paste backfill, *Int. J. Min. Sci. Technol.*, 30(2020), No. 3, p. 271.

[55] H.X. Ding and S.Y. Zhang, Quicklime and calcium sulfoaluminate cement used as mineral accelerators to improve the properties of cemented paste backfill with a high volume of fly ash, *Materials*, 13(2020), No. 18, art. No. 4018.

[56] Z.Q. Huang, E. Yilmaz, and S.A. Cao, Analysis of strength and microstructural characteristics of mine backfills containing fly ash and desulfurized gypsum, *Minerals*, 11(2021), No. 4, art. No. 409.

[57] L. Liu, S.S. Ruan, C.C. Qi, *et al.*, Co-disposal of magnesium slag and high-calcium fly ash as cementitious materials in backfill, *J. Cleaner Prod.*, 279(2021), art. No. 123684.

[58] Y.H. Sheng, G.B. Li, and H.Q. Jiang, Effects of superplasticizers and fly ash on rheological properties of cemented tailings backfill, *J. Chongqing Univ.*, 43(2020), No. 4, p. 60.

[59] H.B. Wei, *Development and Application of Fly Ash-Slag Filling Cementing Materials by High-Value Utilization of Low-Quality Solid Waste* [Dissertation], University of Science and Technology Beijing, Beijing, 2021, p. 51.

[60] X.F. Zhou, C.Y. Lang, X. Chen, and L.Y. Wen, Influence of activator on microstructure of the desulfurization ash cement, *Bull. Chin. Ceram. Soc.*, 34(2015), No. 5, p. 1435.

[61] M. Nag and T. Shimaoka, A novel and sustainable technique to immobilize lead and zinc in MSW incineration fly ash by using pozzolanic bottom ash, *J. Environ. Manage.*, 329(2023), art. No. 117036.

[62] Y.L. Liu, Z.Y. Mo, Y.P. Su, and Y.H. Chen, State-of-the-art controlled low-strength materials using incineration industrial by-products as cementitious materials, *Constr. Build. Mater.*, 345(2022), art. No. 128391.

[63] J.J. Li, E. Yilmaz, and S. Cao, Influence of solid content, cement/tailings ratio, and curing time on rheology and strength of cemented tailings backfill, *Minerals*, 10(2020), No. 10, art. No. 922.

[64] C.D. Min, Y. Shi, and Z.X. Liu, Properties of cemented phosphogypsum (PG) backfill in case of partially substitution of composite Portland cement by ground granulated blast furnace slag, *Constr. Build. Mater.*, 305(2021), art. No. 124786.

[65] Q.S. Chen, Q.L. Zhang, C.C. Qi, A. Fourie, and C.C. Xiao, Recycling phosphogypsum and construction demolition waste for cemented paste backfill and its environmental impact, *J. Cleaner Prod.*, 186(2018), p. 418.

[66] K.W. Rong, W.T. Lan, and H.Y. Li, Industrial experiment of goaf filling using the filling materials based on hemihydrate phosphogypsum, *Minerals*, 10(2020), No. 4, art. No. 324.

[67] W. Chen, S.S. Yuan, and B. Yuan, Development of red mud activated fly ash-based backfilling material and its activation mechanism, *J. Wuhan Univ. Technol.*, 41(2019), p. 20.

[68] J. Zhang, S.C. Li, and Z.F. Li, Investigation the synergistic effects in quaternary binder containing red mud, blast furnace slag, steel slag and flue gas desulfurization gypsum based on artificial neural networks, *J. Cleaner Prod.*, 273(2020), art. No. 122972.

[69] S.A. Li, R. Zhang, R. Feng, B.Y. Hu, G.J. Wang, and H.X. Yu, Feasibility of recycling bayer process red mud for the safety backfill mining of layered soft bauxite under coal seams, *Minerals*, 11(2021), No. 7, art. No. 722.

[70] Z.K. Wang, Y.M. Wang, L.B. Wu, *et al.*, Effective reuse of red mud as supplementary material in cemented paste backfill: durability and environmental impact, *Constr. Build. Mater.*,

328(2022), art. No. 127002.

[71] Y.N. Tang, J.X. Fu, W.D. Song, and Y.F. Zhang, Mechanical properties and crack evolution of interbedded cemented tailings backfill, *Chin. J. Eng.*, 42(2020), No. 10, p. 1286.

[72] X.P. Song, Y.X. Hao, S. Wang, L. Zhang, W. Liu, and J.B. Li, Mechanical properties, crack evolution and damage characteristics of prefabricated fractured cemented paste backfill under uniaxial compression, *Constr. Build. Mater.*, 330(2022), art. No. 127251.

[73] B.Y. Li, J.X. Zhang, H. Yan, N. Zhou, and M. Li, Experimental investigation into the thermal conductivity of gangue-cemented paste backfill in mine application, *J. Mater. Res. Technol.*, 16(2022), p. 1792.

[74] Y.X. Guo, H.Y. Ran, G.R. Feng, X.J. Du, Y.H. Zhao, and W.S. Xie, Deformation and instability properties of cemented gangue backfill column under step-by-step load in constructional backfill mining, *Environ. Sci. Pollut. Res.*, 29(2022), No. 2, p. 2325.

[75] J. Wang, J.X. Fu, and W.D. Song, Mechanical properties and microstructure of layered cemented paste backfill under triaxial cyclic loading and unloading, *Constr. Build. Mater.*, 257(2020), art. No. 119540.

[76] D. Wu, W.T. Hou, S. Liu, and H.B. Liu, Mechanical response of barricade to coupled THMC behavior of cemented paste backfill, *Int. J. Concr. Struct. Mater.*, 14(2020), No. 1, art. No. 39.

[77] J.F. Hou, Z.P. Guo, L.J. Zhao, W.Z. Liu, and Y.X. Zhang, Study on the damage statistical strength criterion of backfill with crack under thermo-mechanical coupling, *Int. J. Green Energy*, 17(2020), No. 8, p. 501.

[78] X.P. Song, J.B. Li, S. Wang, *et al.*, Study of mechanical behavior and cracking mechanism of prefabricated fracture cemented paste backfill under different loading rates from the perspective of energy evolution, *Constr. Build. Mater.*, 361(2022), art. No. 129737.

[79] F.G. Yang, F. Wu, B.G. Yang, L.T. Li, and Q. Gao, Preparation and performance of composite activated slag-based binder for cemented paste backfill, *Chemosphere*, 309(2022), art. No. 136649.

[80] X.P. Song, S. Wang, M. Wei, *et al.*, Response of dynamic mechanical properties of alkali rice straw based cemented tailings backfill under SHPB impact load, *Chin. J. Nonferrous Met.*, 31(2021), No. 9, p. 2583.

[81] H. Kolsky, An investigation of the mechanical properties of materials at very high rates of loading, *Proc. Phys. Soc.: Sect. B*, 62(1949), No. 11, p. 678.

[82] X.B. Li, Z.L. Zhou, Z.Y. Ye, *et al.*, Study of rock mechanical characteristics under coupled static and dynamic loads, *Chin. J. Rock Mech. Eng.*, 27(2008), No. 7, p. 1390.

[83] K. Liu, Q.B. Zhang, G. Wu, J.C. Li, and J. Zhao, Dynamic mechanical and fracture behaviour of sandstone under multiaxial loads using a triaxial Hopkinson bar, *Rock Mech. Rock Eng.*, 52(2019), No. 7, p. 2178.

[84] B.P. Zou, Z.Y. Luo, F.J. Xu, H.N. Ding, Z.G. Tao, and M.C. He. Experimental study on impact dynamic characteristics of deep sandstone under thermal-hydraulic-mechanical coupling conditions, *Chin. J. Rock Mech. Eng.*, 39(2020), No. 9, p. 1750.

[85] K.W. Xia, S. Wang, Y. Xu, R. Chen, and B.B. Wu, Advances in experimental studies for deep rock dynamics, *Chin. J. Rock Mech. Eng.*, 40(2021), No. 3, p. 448.

[86] J.H. Hu, Z. Tao, X.T. Ding, G.P. Wen, Z.S. Wen, and M.M. Guo, Dynamic response mechanism of a rock-filling interfacial coupling body to blasting in it, *Explos. Shock Waves*, 41(2021), No. 8, p. 164.

[87] F.Q. Gong, X.F. Si, X.B. Li, and S.Y. Wang, Dynamic triaxial compression tests on sandstone at high strain rates and low confining pressures with split Hopkinson pressure bar, *Int. J. Rock Mech. Min. Sci.*, 113(2019), p. 211.

[88] D. Zheng, W.D. Song, S. Cao, and J.J. Li, Dynamical mechanical properties and microstructure characteristics of cemented tailings backfill considering coupled strain rates and confining pressures effects, *Constr. Build. Mater.*, 320(2022), art. No. 126321.

[89] P. Wang, T.B. Yin, and B.W. Hu, Dynamic tensile strength and failure mechanisms of thermally treated sandstone under dry and water-saturated conditions, *Trans. Nonferrous Met. Soc. China*, 30(2020), No. 8, p. 2217.

[90] S. Cao, *Research on Structural Characteristics and Dynamic Effects of Cemented Tailings Backfilling and Its Application* [Dissertation], University of Science and Technology Beijing, Beijing, 2017, p. 58.

[91] G.L. Xue, E. Yilmaz, G.R. Feng, S. Cao, and L.J. Sun, Reinforcement effect of polypropylene fiber on dynamic properties of cemented tailings backfill under SHPB impact loading, *Constr. Build. Mater.*, 279(2021), art. No. 122417.

[92] E.Y. Liu, Q.L. Zhang, Y. Feng, and J.W. Zhao, Experimental study of static and dynamic mechanical properties of double-deck backfill body, *Environ. Earth Sci.*, 76(2017), No. 20, art. No. 689.

[93] X. Chen, X.Z. Shi, J. Zhou, E.M. Li, P.Y. Qiu, and Y.G. Gou, High strain rate compressive strength behavior of cemented paste backfill using split Hopkinson pressure bar, *Int. J. Min. Sci. Technol.*, 31(2021), No. 3, p. 387.

[94] W. Yang, Q.L. Zhang, S. Yang, and X.M. Wang, Mechanical property of high concentration total tailing cemented backfilling under dynamic loading, *J. Cent. South Univ. Sci. Technol.* 48(2017), No. 1, p. 156.

[95] Y.F. Hu, K.Q. Li, B. Han, H.Y. Li, and J.T. Zhao, Strength development and optimization analysis of mixed aggregate backfill based on RSM-DF, *J. Cent. South Univ. Sci. Technol.*, 53(2022), No. 2, p. 620.

[96] J.Y. Wu, H.W. Jing, Q. Yin, B. Meng, and G.S. Han, Strength and ultrasonic properties of cemented waste rock backfill considering confining pressure, dosage and particle size effects, *Constr. Build. Mater.*, 242(2020), art. No. 118132.

[97] Y.H. Zhao, Y.X. Guo, G.R. Feng, C.Q. Li, W.S. Xie, and C.L. Zhang, Study on strength and deformation characteristics of cemented gangue backfill body under the coupling action of load and salt erosion, *Constr. Build. Mater.*, 342(2022), art. No. 128003.

[98] B. Koohestani, A.K. Darban, E. Darezereshki, P. Mokhtari, E. Yilmaz, and E. Yilmaz, The influence of sodium and sulfate ions on total solidification and encapsulation potential of iron-rich acid mine drainage in silica gel, *J. Environ. Chem. Eng.*, 6(2018), No. 2, p. 3520.

[99] N. Zhou, C.W. Dong, J.X. Zhang, G.H. Meng, and Q.Q. Cheng, Influences of mine water on the properties of construction and demolition waste-based cemented paste backfill, *Constr. Build. Mater.*, 313(2021), art. No. 125492.

[100] G.Z. Jiang, A.X. Wu, H. Li, Y.M. Wang, and H.J. Wang, Long-term strength performance of sulfur tailings filling and its affecting factors, *J. Cent. South Univ. Sci. Technol.*, 49(2018), No. 6, p. 1504.

[101] Z.W. Du, S.J. Chen, D.W. Yin, D.H. Yao, and Z. Zhang, Experimental study of stability of paste backfill under chloride erosion environment, *J. China Univ. Min. Technol.*, 50(2021), No. 3, p. 532.

[102] M. Tao, D.M. Lu, Y. Shi, and C.Q. Wu, Utilization and life cycle assessment of low activity solid waste as cementitious materials: A case study of titanium slag and granulated blast furnace slag, *Sci. Total Environ.*, 849(2022), art. No. 157797.

[103] Z.G. Xiu, S.H. Wang, Y.C. Ji, F.L. Wang, and F.Y. Ren, Experimental study on the triaxial mechanical behaviors of the

cemented paste backfill: Effect of curing time, drainage conditions and curing temperature, *J. Environ. Manage.*, 301(2022), art. No. 113828.

[104] T. Kasap, E. Yilmaz, N.U. Guner, and M. Sari, Recycling dam tailings as cemented mine backfill: Mechanical and geotechnical properties, *Adv. Mater. Sci. Eng.*, 2022(2022), art. No. 6993068.

[105] X.M. Wei, L.J. Guo, C.H. Li, L.X. Zhang, W.C. Luo, and R. Liu, Study of space variation law of strength of high stage cemented backfill, *Rock Soil Mech.*, Suppl.2(2018), p. 45.

[106] G.C. Zhang, Z.Q. Yang, Q. Gao, G.L. Xue, and S.H. Yin, Study on *in-situ* backfilling test with total tailings from iron mine with tailings consolidation powder, *Min. Metall. Eng.*, 34(2014), No. 3, p. 19.

[107] T. Belem and M. Benzaazoua, Design and application of underground mine paste backfill technology, *Geotech. Geol. Eng.*, 26(2008), No. 2, p. 175.

[108] D.Q. Gan, Y.J. Zhang, Z.Y. Liu, and H.K. Sun, Study on multi-scale mechanical properties of cemented backfill under different curing ages, *Min. Res. Develop.*, 42(2022), No. 12, p. 7.

[109] A.A. Wang, S. Cao, and E. Yilmaz, Effect of height to diameter ratio on dynamic characteristics of cemented tailings backfills with fiber reinforcement through impact loading, *Constr. Build. Mater.*, 322(2022), art. No. 126448.

[110] Y.B. Hu, W.P. Li, X.M. Chen, H.Z. Xu, and S.L. Liu, Temporal and spatial evolution characteristics of fracture distribution of floor strata in deep coal seam mining, *Eng. Fail. Anal.*, 132(2022), art. No. 105931.

[111] C.X. Liu, J.Q. Jiang, F.S. Liu, and S.H. Wang, Fractal study of scale effect in microscopic, mesoscopic and macroscopic states for fracture mechanism of rock materials, *Rock Soil Mech.*, 29(2008), No. 10, p. 2619.

[112] B. Pal and A. Ramaswamy, A multi-physics-based approach to predict mechanical behavior of concrete element in a multi-scale framework, *Mech. Mater.*, 176(2023), art. No. 104509.

[113] K. Zhao, J. Wu, Y.J. Yan, Y. Zhou, J. Yang, and Z.W. He, Multi-scale characteristics of crack evolution of cemented tailings backfill, *Chin. J. Rock Mech. Eng.*, 41(2022), No. 8, p. 1626.

[114] Y.H. Zhao, H.Y. Ran, G.R. Feng, Y.X. Guo, and Y.J. Fan, Damage evolution and failure characteristics of cemented gangue backfill body with different height-width ratios under uniaxial compression, *J. Min. Safety Eng.*, 39(2022), No. 4, p. 674.

[115] X.P. Song, Y.X. Hao, S. Wang, *et al.*, Dynamic mechanical response and damage evolution of cemented tailings backfill with alkalized rice straw under SHPB cycle impact load, *Constr. Build. Mater.*, 327(2022), art. No. 127009.

[116] S. Cao, G.L. Xue, and E. Yilmaz, Flexural behavior of fiber reinforced cemented tailings backfill under three-point bending, *IEEE Access*, 7(2019), p. 139317.

[117] K. Zhao, X. Yu, S.T. Zhu, *et al.*, Acoustic emission fractal characteristics and mechanical damage mechanism of cemented paste backfill prepared with tantalum niobium mine tailings, *Constr. Build. Mater.*, 258(2020), art. No. 119720.

[118] L. Liu, M. Yang, X.B. Zhang, J.R. Mao, and P. Chai, LNMR experimental study on the influence of gas pressure on methane adsorption law of middle-rank coal, *J. Nat. Gas Sci. Eng.*, 91(2021), art. No. 103949.

[119] W. Sun, A.X. Wu, K.P. Hou, Y. Yang, and L. Liu, Application of X-Ray CT technology in the pore structure study of subsidence area backfilling body, *Rock Soil Mech.*, 38(2017), No. 12, p. 3635.

[120] Y. Wang, H.J. Wang, X.L. Zhou, X.F. Yi, Y.G. Xiao, and X.M. Wei, *In situ* X-ray CT investigations of meso-damage evolution of cemented waste rock-tailings backfill (CWRTB) during triaxial deformation, *Minerals*, 9(2019), No. 1, art. No. 52.

[121] X.F. Yi, C.K. Liu, and Y. Wang, Experimental study on the fracture evolution of cemented waste rock-tailings backfill (CWRB) of metal ore using *in-situ* CT scanning, *Rock Soil Mech.*, 41(2020), No. 10, p. 3365.

[122] A.E. Belibi Tana, S.H. Yin, and L.M. Wang, Investigation on mechanical characteristics and microstructure of cemented whole tailings backfill, *Minerals*, 11(2021), No. 6, art. No. 592.

[123] D.J. Zou, Z.C. Que, W. Cui, X. Wang, Y.H. Guo, and S.D. Zhang, Feasibility of recycling autoclaved aerated concrete waste for partial sand replacement in mortar, *J. Build. Eng.*, 52(2022), art. No. 104481.

[124] F. Du, K. Wang, X.L. Dong, and J.P. Wei, Numerical simulation of damage and failure of coal-rock combination based on CT three-dimensional reconstruction, *J. China Coal Soc.*, 46(2021), No. 1, p. 253.

[125] T.Y. Wei, X.H. Wang, T. Lv, D.W. Hu, H. Zhou, and W. Hong, Analysis of the influence of wetting expansion and sand mixing rate on the THM coupling process of hybrid buffer material, *Rock Soil Mech.*, 43(2022), No. 2, p. 549.

[126] H. Zhang, S. Cao, and E. Yilmaz, Carbon nanotube reinforced cementitious tailings composites: Links to mechanical and microstructural characteristics, *Constr. Build. Mater.*, 365(2023), art. No. 130123.

[127] M. Sari, E. Yilmaz, T. Kasap, and N.U. Guner, Strength and microstructure evolution in cemented mine backfill with low and high pH pyritic tailings: Effect of mineral admixtures, *Constr. Build. Mater.*, 328(2022), art. No. 127109.

[128] B.W. Wang, L.J. Gao, W.H. Zhao, Y.N. Li, W. Ding, and Z. Li, Microscopic experiment of consolidating tailings by Linglong cementitious material, *Int. J. Min. Sci. Technol.*, 4(2019), No. 6, p. 524.

[129] B.X. Yan, H.W. Jia, E. Yilmaz, X.P. Lai, P.F. Shan, and C. Hou, Numerical study on microscale and macroscale strength behaviors of hardening cemented paste backfill, *Constr. Build. Mater.*, 321(2022), art. No. 126327.

[130] A. Loykaew and S. Utara, Effect of acidic and sulfated environments on phase transformation, compressive strength and microstructure of natural rubber latex-modified cement pastes, *J. Mater. Res. Technol.*, 9(2020), No. 6, p. 15496.

[131] W.B. Xu, B. Liu, and W.L. Wu, Strength and deformation behaviors of cemented tailings backfill under triaxial compression, *J. Cent. South Univ.*, 27(2020), No. 12, p. 3531.

[132] China State Administration for Market Regulation and China National Standardization Administration, GB/T 39489-2020: *Technical Specification for the Total Tailings Paste Backfill*, China Quality and Standards Publishing & Media Co., Ltd, Beijing, 2020.

[133] Ministry of Construction of the People's Republic of China and China State General Administration for Quality Supervision and Inspection and Quarantine, GB/T 50080-2016: *Standard for Test Method of Performance on Ordinary Fresh Concrete*, China Quality and Standards Publishing & Media Co., Ltd, Beijing, 2020.

[134] Z.P. Yan, S.H. Yin, X. Chen, and L.M. Wang, Rheological properties and wall-slip behavior of cemented tailing-waste rock backfill (CTWB) paste, *Constr. Build. Mater.*, 324(2022), art. No. 126723.

[135] B.Q. Yan, F.H. Ren, M.F. Cai, and C. Qiao, Influence of new hydrophobic agent on the mechanical properties of modified cemented paste backfill, *J. Mater. Res. Technol.*, 8(2019), No. 6, p. 5716.

[136] C.C. Qi and A. Fourie, Cemented paste backfill for mineral tailings management: Review and future perspectives, *Miner. Eng.*, 144(2019), art. No. 106025.

[137] Z.Q. Huang, S. Cao, and E. Yilmaz, Investigation on the flexural strength, failure pattern and microstructural characteristics of combined fibers reinforced cemented tailings backfill, *Constr. Build. Mater.*, 300(2021), art. No. 124005.

[138] D.V. Boger, Rheology of slurries and environmental impacts in the mining industry, *Annu. Rev. Chem. Biomol. Eng.*, 4(2013), p. 239.

[139] S.H. Yin, J.M. Liu, W. Chen, Y.J. Shao, L.B. Wu, and X.T. Wang, Rheological properties of coarse aggregate at low temperature and its regression models, *J. Cent. South Univ. Sci. Technol.*, 51(2020), No. 12, p. 3379.

[140] F. Wu, F.H. Yang, B.L. Xiao, and Q. Gao, Characterization of rheological property and its application of high concentration and mixed aggregate filling slurry based on spread, *J. Cent. South Univ. Sci. Technol.*, 53(2022), No. 8, p. 3104.

[141] L. Liu, Z.Y. Fang, Y.P. Wu, X.P. Lai, P. Wang, and K.I.I L. Song, Experimental investigation of solid-liquid two-phase flow in cemented rock-tailings backfill using electrical resistance tomography, *Constr. Build. Mater.*, 175(2018), p. 270.

[142] W.T. Lan and A.X. Wu, Derivation and test verification of general equation for pipeline laminar flow, *J. Huazhong Univ. Sci. Technol.*, 47(2019), No. 11, p. 61.

[143] X.B. Yang, Z.P. Yang, S.H. Yin, and H. Yang, Transportation pressure model and optimization of coarse aggregate paste backfill based on pipe loop test, *J. Hunan Univ.* (*Natural Sci.*), 49(2022), No. 5, p. 183.

[144] Y. Zhao, G.Y. Zhao, D.F. Pei, P. Wu, J. Qiu, and Y. Li, Analysis on connotation, characteristics and type of green mining mode for underground metal mines, *Chin. J. Nonferrous Met.*, 31(2021), No. 12, p. 3700.

[145] G.Y. Zhao, P. Wu, D.F. Pei, and Y. Zhao, Study on the mining mode in deep metal mines and its technological system based on green mining, *Gold*, 41(2020), No. 9, p. 58.

[146] X. Lin, Y. Zhang, Q. Liu, and R. Ou, Thoughts on the layout of mineral resources development under carbon peak and carbon neutrality goals, *Min. Res. Develop.*, 42(2022), No. 6, p. 153.

[147] Q.S. Chen, L.M. Zhu, Y.M. Wang, J. Chen, and C.C. Qi, The carbon uptake and mechanical property of cemented paste backfill carbonation curing for low concentration of CO_2, *Sci. Total Environ.*, 852(2022), art. No. 158516.

[148] L.J. Su, G.S. Fu, Y.L. Wang, *et al.*, Preparation and performance of a low-carbon foam material of fly-ash-based foamed geopolymer for the goaf filling, *Materials*, 13(2020), No. 4, art. No. 841.

[149] J.P. Qiu, Y.L. Zhao, H. Long, Z.B. Guo, J. Xing, and X.G. Sun, Low-carbon binder for cemented paste backfill: Flowability, strength and leaching characteristics, *Minerals*, 9(2019), No. 11, art. No. 707.

[150] Ministry of Natural Resources of the People's Republic of China, *Five-year National Plan on Mineral Resources (2016—2020)*, Ministry of Natural Resources of the People's Republic of China, Beijing, 2016.

[151] T. Henckens, Scarce mineral resources: Extraction, consumption and limits of sustainability, *Resour. Conserv. Recycl.*, 169(2021), art. No. 105511.

[152] H.Y. Zhu, D.D. Zhang, H.H. Goh, *et al.*, Future data center energy-conservation and emission-reduction technologies in the context of smart and low-carbon city construction, *Sustain. Cities Soc.*, 89(2023), art. No. 104322.

[153] H.S. Ge, F.H. Gong, Y.Y. Sun, *et al.*, Construction and application of intelligent system in open-pit mine under dual 5G network, *Met. Mine*, 9(2022), p. 167.

[154] Z.Q. Wang, Z.J. Qi, Y.P. Kou, J.G. Yang, Z.P. Song, and H.B. Jia, Intelligent filling system enabling new development of mine, *Min. Res. Develop.*, 42(2022), No. 1, p. 156.

[155] X.Z. Chen, X.C. Yang, L.J. Guo, W.Y. Xu, and C.X. Shi, Intelligent control system design on mine filling and engineering applications, *Nonferrous Met. Eng.*, 12(2022), No. 2, p. 114.

[156] H. Chang, Z.K. Zhu, B.S. Gu, *et al.*, A study of strength prediction of steel slag tailings-slag based filler based on BP neural network, *J. Anhui Univ. Technol. Nat. Sci.*, 39(2022), No. 3, p. 256.

[157] J.D, Liu. *Thick-Hard Roof Subsidence Control for Slowly Inclined Large-Thick Ore Body Under High Tectonic Stress and Its Interaction Mechanism with Backfilling Body* [Dissertation]. China University of Mining and Technology, Xuzhou, 2020, p. 24.

[158] J.P. Qiu, Z.B. Guo, L. Li, S.Y. Zhang, Y.L. Zhao, and Z.Y. Ma, A hybrid artificial intelligence model for predicting the strength of foam-cemented paste backfill, *IEEE Access*, 8(2020), p. 84569.

[159] S.K. Behera, D.P. Mishra, P. Singh, *et al.*, Utilization of mill tailings, fly ash and slag as mine paste backfill material: Review and future perspective, *Constr. Build. Mater.*, 309(2021), art. No. 125120.

[160] Z.J. Wang, Y.P. Kou, Z.B. Wang, Z.H. Wu, and J.R. Guo, Random forest slurry pressure loss model based on loop experiment, *Minerals*, 12(2022), No. 4, art. No. 447.

[161] Y.P. Kou, Y.H. Liu, G.Q. Li, J.E. Hou, L.M. Luan, and H. Wang, Design and implementation of an integrated management system for backfill experimental data, *Adv. Civ. Eng.*, 2022(2022), art. No. 1876435.

[162] W.Z Sha, C. Zhang, Z. Peng, Y.H. Wei, K. Chen, Refined scanning and modeling technology of chute in Prang Copper Mine, *Min. Metall.* 29(2020), No. 1, p. 5.

[163] Q.F. Guo, M.F. Cai, X.H. Wu, X. Xi, M.H. Ma, and J. Zhang. Technological strategies for intelligent mining subject to multifield couplings in deep metal mines toward 2035, *Chin. J. Eng.*, 44(2022), No. 4, p. 476.

[164] S.M. Chen, W. Wang, R.F. Yan, A.X. Wu, Y.M. Wang, and E. Yilmaz, A joint experiment and discussion for strength characteristics of cemented paste backfill considering curing conditions, *Minerals*, 12(2022), No. 2, art. No. 211.

[165] A. Ghirian and M. Fall, Strength evolution and deformation behaviour of cemented paste backfill at early ages: Effect of curing stress, filling strategy and drainage, *Int. J. Min. Sci. Technol.*, 26(2016), No. 5, p. 809.

[166] W.Z. Liu, Z.P. Guo, W.P. Huang, S.W. Niu, and J.F. Hou. Experimental study on mechanical characteristics of cemented backfill under triaxial unloading confining pressure after cured at different temperatures, *Chin. J. Rock Mech. Eng.*, 41(2022), No. 11, p. 2279.

[167] C. Yang, P. Yang, W.S. Lv, and Z.K. Wang, Mechanical performance of confined consolidation on the strength development of cemented paste backfill, *Geotech. Geol. Eng.*, 38(2020), No. 2, p. 1097.

[168] F.F. Jiang, H. Zhou, J. Sheng, X.D. Li, and Y.Y. Kou, Temperature effect on shear behavior of ore-backfill coupling specimens at various shear directions, *J. Cent. South Univ.*, 28(2021), No. 10, p. 3173.

[169] L.S. Liu, X.C. Yang, C.C. Wan and Y.C. Zhou., Research progress on mechanical problems in deep mining of metal mines, *Nonferrous Met. Min. Sec.*, 74(2022), No. 4, p. 14.

[170] X.B. Li, Z.W. Cao, J. Zhou, *et al.*, Innovation of mining models and construction of intelligent green mine in hard rock mine: In Kaiyang phosphate mine as an example, *Chin. J. Nonferrous Met.*, 29(2019), No. 10, p. 2364.

[171] A.A. Wang, S. Cao, and E. Yilmaz, Influence of types and contents of nano cellulose materials as reinforcement on stability performance of cementitious tailings backfill, *Constr. Build. Mater.*, 344(2022), art. No. 128179.

[172] Y. Wang, Q. Na, and L.F. Zhang, Monitoring of *in situ* proper-

ties for cemented tailings backfill that under drainage condition, *Constr. Build. Mater.*, 356(2022), art. No. 129254.

[173] S. Cao, D. Zheng, E. Yilmaz, Z.Y. Yin, G.L. Xue, and F.D. Yang, Strength development and microstructure characteristics of artificial concrete pillar considering fiber type and content effects, *Constr. Build. Mater.*, 256(2020), art. No. 119408.

[174] S.A. Ghoreishi-Madiseh, F. Hassani, and F. Abbasy, Numerical and experimental study of geothermal heat extraction from backfilled mine stopes, *Appl. Therm. Eng.*, 90(2015), p. 1119.

[175] X.Y. Zhang, D. Wen, Y.J. Zhao, *et al.*, Thermal-mechanical properties and heat transfer process of heat storage/energy storage backfill body in mine, *J. China Coal Soc.*, 46(2021), No. 6, p. 3158.

[176] B.X. Yan, W.C. Zhu, C. Hou, E. Yilmaz, and M. Saadat, Characterization of early age behavior of cemented paste backfill through the magnitude and frequency spectrum of ultrasonic P-wave, *Constr. Build. Mater.*, 249(2020), art. No. 118733.

[177] H.P. Xie, Y. Ju, F. Gao, M.Z. Gao, and R. Zhang, Groundbreaking theoretical and technical conceptualization of fluidized mining of deep underground solid mineral resources, *Tunn. Undergr. Space Technol.*, 67(2017), p. 68.

[178] B.Q. Wu, X.D. Wang, X.X. Liu, G.G. Xu, and S.B. Zhu, Numerical simulation of erosion and fatigue failure the coal gangue paste filling caused to pumping pipes, *Eng. Fail. Anal.*, 134(2022), art. No. 106081.