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Mechanical behaviours and backfilling performance of cemented tailings-waste rock backfill with various superplasticisers: an experimental study

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Abstract

Cemented paste backfill (CPB) is an artificial product that exhibits superior mechanical properties. The compressive strength and fluidity of CPB are critical design factors that affect its backfilling performance. However, the maldistribution of backfill strength and poor slurry fluidity are still major problems for the backfilling of mined-out area in Jinchuan nickel mine. In this paper, four types of superplasticisers, polycarboxylate- (PC-P), naphthalene- (FDN), aliphatic- (AK) and melamine-based (SM), were investigated to analyse the mechanical behaviour of CPB with tailings-waste rock (TW). Firstly, primary focus was on the proportioning test of CPB-TW, and an optimal ratio was subsequently determined for the optimisation test of superplasticisers. The findings demonstrated that CPB-TW had optimal backfilling performance as the cement-sand ratio was 1:4, slurry concentration was 77%, and the amount of waste rock (WR) was 60%. Under this condition, the specimen had the highest unconfined compressive strength (UCS) values of 1.17 MPa and 5.03 MPa at three and 28 days, respectively. The superplasticisers dosage ranged from 0.15 to 1.2% (by mass of cements) and was subjected to the above-optimised CPB-TW slurry to test the setting time, slump evolution, microstructure, and UCS. Test results indicated that the appropriate superplasticisers can effectively improve the free water distribution in CPB-TW slurry and facilitate the transportation of slurry in the backfilling pipeline. Otherwise, excessive addition of superplasticisers will significantly degrade the backfilling performance of CPB-TW. Comprehensively, CPB-TW with PC-P (cement content × 0.35%) had the optimal slurry slump, UCS, and the better coagulation performance, which is conducive to the pipeline transportation of backfilling slurry.

Keywords: *mechanical behaviour, backfilling performance, cemented paste backfill, pipeline transportation, superplasticisers*

1 Introduction

Bulk mineral solid waste (BMSW) is an inexorable byproduct of mineral mining and metallurgical production that urgently needs to be profitably and harmlessly utilised (Wang et al. 2022; Mkahal et al. 2022). It is considered that waste rock (WR) and tailings are the main formation of BMSW (Yan et al. 2022; Yin et al. 2022). Moreover, ultrafine grinding is an efficient technology to improve the ore recovery, resulting in the gradual refinement of the tailings particle size. High doses of cement and chemical agents are also used in the traditional BMSW utilisation process (Yin et al.2023). The current 'bottleneck' problems are the difficulty of disposal, high carbon emissions, substantial process costs, serious potential pollution, and low utilisation rate of solid waste. As a result, serious secondary pollution and personnel safety hazards are prone to occur due to the above issues. One way to overcome these problems is to apply the cemented backfill mining method for underground mining activities (Fang et al. 2023; Pan et al. 2023).

As a cement-based material, the mechanical properties of CPB-TW are very similar to those of concrete (Sun et al. 2023). During the long-term backfilling practice, it is generally believed that the backfill strength is positively correlated with the cement-sand ratio, slurry mass concentration and curing age (Hu et al. 2023). The slurry fluidity deteriorates with the increase of cement content and slurry mass concentration. Contrary to the above findings, the slurry fluidity and backfill strength of CPB can be improved to a certain degree by adding a suitable amount of WR and chemical admixture (Yang et al. 2015).

However, there is still a serious problem with the pipeline transportation of backfilling slurry in Jinchuan nickel mine, which is the high content of fine particles, resulting in poor fluidity of the CPB slurry. It is acknowledged that the fluidity of backfilling slurry is mainly affected by the slurry concentration, sand-cement ratio, and the properties of aggregates (Yang et al. 2023). Slurry fluidity test is a method that can comprehensively investigate its fluid performance. It was found that appropriate superplasticisers can effectively improve the fluidity of CPB slurry and its transportation resistance. However, there are a wide variety of superplasticisers with different function mechanisms (Li et al. 2023; Jouneghani et al. 2023). Thus, it is necessary to select the optimal type and dosage of superplasticisers for the tailings with different particle size distributions and types.

Superplasticiser, as a superior concrete admixture, is mainly used to reduce the initial amount of water added to cement mortar, making it have good fluidity. The decrease in free water content (or increase in solid volume fraction) leads to a decrease in the porosity of hardening materials and an increase in mechanical strength. As a result, the workability of concrete has been significantly improved. It is acknowledged that different superplasticisers have varying effects on the performance of concrete and there are four mainstream superplasticisers suitable for underground mined-out area backfilling. The raw materials of polycarboxylate superplasticiser (PC-P) mostly contain functional groups with different functions, and the molecules are composed of main chains containing carboxylic acid groups and oxygen-containing long side chains. The comb type molecules have high designability, which determines that PC-P can develop series products with different performance characteristics (Mardani-Aghabaglou et al. 2013; Ma et al. 2020).

Related research proves that naphthalene superplasticiser (FDN) have strong adaptability to different types of cement and have no corrosion effect on steel bars. It can be used to prepare early-strength, high-strength, and steam-cured concrete, as well as to prepare vibration free self-compacting concrete (Boukendakdji et al. 2012; Tan et al. 2014). There are also many studies on the service performance of melamine-based superplasticiser (SM). Yan et al. (2023) considered that SM can be dissolved in the alkaline environment of cement slurry and dissociated into charged anions ($M\text{-}SO_3^{2-}$) and cations (Na^+). Furthermore, the molecule of SM is directionally adsorbed on the surface of cement particles, causing the surface of cement particles to carry charges with the same electrical properties. And the amount of charge increases with the increase of superplasticiser concentration until saturation. Due to the action of electric charges between cement particles, electrostatic repulsion is generated. Thus, the cement–water system is in a relatively stable suspended state caused by the effect of electric repulsion. As a result, the agglomeration between cement particles is weakened, while the polar groups that do not interact with the surface of cement particles extend into the liquid phase with the hydrocarbon chain, allowing the cement particles to disperse and exhibit superior fluidity (Yin et al. 2021).

The objective of this paper is to investigate the effect of slurry concentration, cement-sand ratio, and superplasticiser dosage on the fluidity of CPB-TW slurry, as well as the improvement effect of superplasticiser on the backfilling performance. In the preliminary exploration experiment, the optimum proportion of CPB-TW was determined by setting different condition gradients of cement–sand ratio (designed as 1:4, 1:5, and 1:6), slurry mass concentration (designed as 76, 77 and 78%), and WR content (designed as 50, 60 and 70%). Subsequently, four types of superplasticisers with different dosages were added to the CPB-TW slurry, and it was found that CPB-TW added with 0.35% dosage of PC-P had the best mechanical properties and backfilling performance. The research results can provide theoretical basis for guiding the design of slurry preparation and reduced pipeline friction losses in Jinchuan nickel mine.

2 Methods and materials

2.1 Materials

Tailings, WR, composite Portland cement (P.C) and superplasticiser were selected as the experimental materials for preparing backfill. P.C was obtained from the cement factory in Jinchuan Nickel Mine, China. To ensure the continuity of particle size gradation, the slurry tailings were directly extracted and dried as experimental materials in the mineral processing plant. Superplasticisers were purchased from Muhu Agents, China, including polycarboxylate superplasticiser (PC-P), naphthalene superplasticiser (FDN), aliphatic superplasticiser (AK) and melamine-based superplasticiser (SM).

2.1.1 Superplasticisers

Superplasticiser, a chemical admixture, is frequently used in slurry preparation, which can significantly increase the slurry slump and fluidity. Furthermore, the strength and stability of backfill can be improved by adding appropriate superplasticiser. PC-P, FDN, AK and SM are synthesised by manufacture through optimised processes, thus each superplasticiser has its appropriate dosage range. The main ingredient and technical index of superplasticisers used in this paper are shown in Table 1.

Table 1 Superplasticisers main ingredient and technical index

Type	PH of 10 g/L solution	Total alkali content (Na_2O+0.658K_2O)/%	Chloride ion content/%	Sodium sulphate content/%	Fluidity of cement paste/mm	Admixture volume/%
PC-P	6~7	≤0.2	≤0.02	≤2.5	≥250	$V_{P.C}$×(0.1~0.5%)
FDN	7~9	≤4	<0.3	≤5	≥250	$V_{P.C}$×(0.4~1%)
AK	7~9	≤18	≤0.1	0.82	≥240	$V_{P.C}$×(0.3~1.2%)
SM	7~9	≤10	≤0.2	0.93	≥240	$V_{P.C}$×(0.3~1.2%)

2.1.2 Materials particle size distribution and physical properties

LMS-30 laser particle size analyser (Fresh Co. Ltd, Japan) was used for performance measurement of the full tailings with size of 0.1~500 µm. The artificial standard sieves (Zhuohang Co. Ltd, China) with various mesh sizes were used to measure the WR particle size. Phenom XL G2 desktop scanning electron microscope (Phenom-World Co. Ltd, Netherlands) was used to analyse the microscopic morphology of materials. It can be seen from Figure 1a that the -79.62 µm fraction accounts for about 91.31% of the total tailing, which is a superfine tailing with a curvature coefficient of 1.237, between 1 and 3, indicating a good continuity of the superfine tailings particle size gradation. Figure 1b shows that the maximum particle size of WR is 20 mm. The major particle sizes range from 0.2 to 10 mm, in which the median particle size is 5.43 mm. The microscopic morphology of the materials was assessed using a scanning electron microscope (SEM), the tailings are irregular in shape, mostly in the form of flakes and blocks, appearing circular and only occupying a small part. The particle size distribution is uneven and extremely fine flocculent substances adhere to the surface of coarse particles (Figure 1c). Furthermore, the WR has a laminar and columnar structure with a rough surface throughout (Figure 1d). The rough surface texture helps the materials engage with each other and contributes to the strength of the CPB.

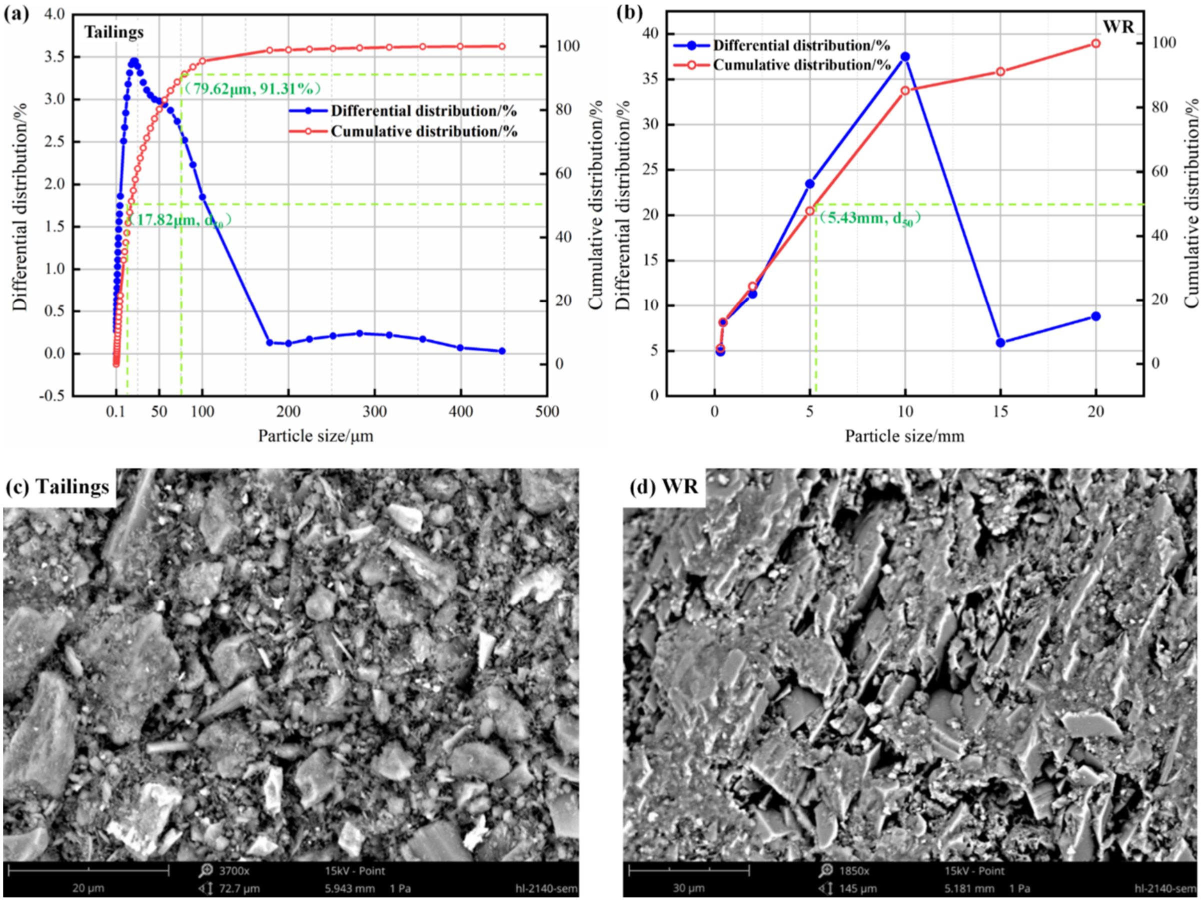

Figure 1 Materials particle size distribution and microscopic morphology

According to GB-T14684-2022 *Basic Physical Properties Test of the Sand For Construction* (Chen 2019), the relevant physical property tests of materials were performed for the experimental design, as shown in Table 2.

Table 2 Materials physical properties

Materials	Specific gravity ($N \cdot m^{-3}$)	Bulk density ($t \cdot m^{-3}$)		Packing density (%)		Porosity (%)	
		Loose	Dense	Loose	Dense	Loose	Dense
Tailings	2.7293×10^4	1.2173	1.527	43.7	54.8	56.29	45.17
WR	2.7499×10^4	1.675	1.968	59.7	70.1	40.31	29.86

2.1.3 Material chemical element and mineral composition

The XRD-Rigaku-BLKD analyser (Rigaku Co. Ltd, Japan) was used to determine the materials mineral composition. The XRF-1800 X-ray fluorescence spectrometer (Shimadzu Co. Ltd, Japan) was used to analyse the materials chemical element composition, as shown in Figure 2. The results showed that the tailings were mainly composed of SiO_2 (36.85%), MgO (34.17%), Fe_2O_3 (15.54%), and Al_2O_3 (3.61%), and the WR was mainly composed of SiO_2 (42.18%), CaO (21.08%), MgO (13.64%), and Al_2O_3 (8.85%). All backfill materials feature SiO_2 and Al_2O_3 as potential gelling ingredients, and they are all more desired backfill materials since S, which reduces backfill strength, is extremely low, and Zn, which slows the pastedown, is only slightly higher.

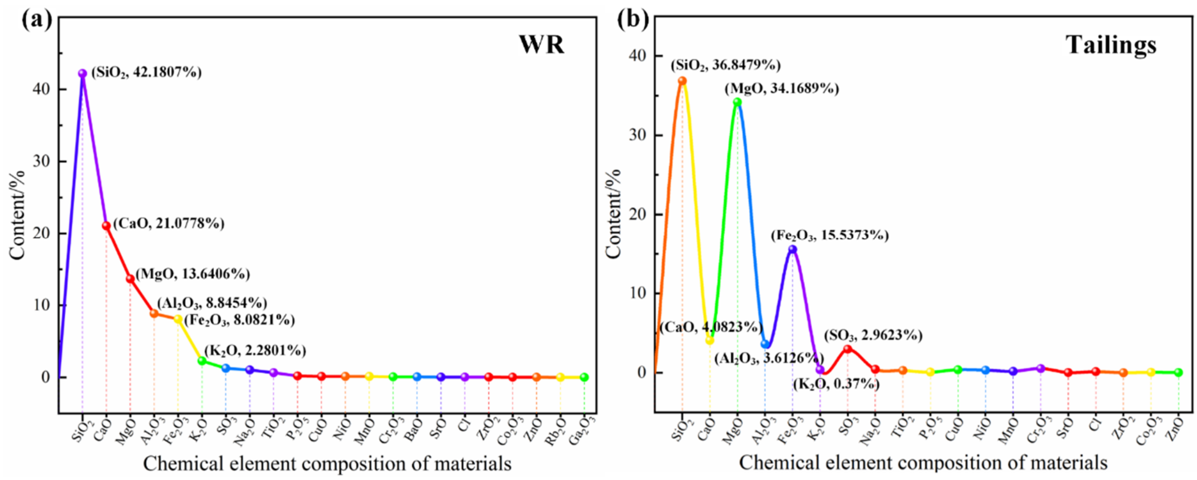

Figure 2 Chemical element composition of materials

2.2 Experimental

2.2.1 Unconfined compressive strength test

According to JG3019 *Specification for Concrete Mould Test* (Gan et. al 2024), the backfill slurry was poured into a standard test mould with polished inner surface that was 70.7 mm in length, 70.7 mm in height, and 70.7 mm in breadth. After standing for 24 hours at room temperature, the specimens were numbered and demolded. A standard curing room with temperature of (20±2) C and relative humidity of more than 90% was used for curing the specimens. The experimental process and main measurement methods were shown in Figure 3.

UCS tests were carried out at the curing ages of 3, 7 and 28 days, respectively. Material proportioning scheme of the test specimens is shown in Table 3. The dosage of superplasticiser mentioned in the paper was by the mass of cement content. The superplasticiser was added to clean water according to the design amount and stirred well before being added to the CPB-TW slurry. Press equipment for the WEW-600D hydraulic universal testing machine, which has a maximum load of 600 kN and a resolution of 0.1 kN. 0.25–1.5 kN of test process load are applied every second. The ends of the specimen were polished to provide a flat surface before the test.

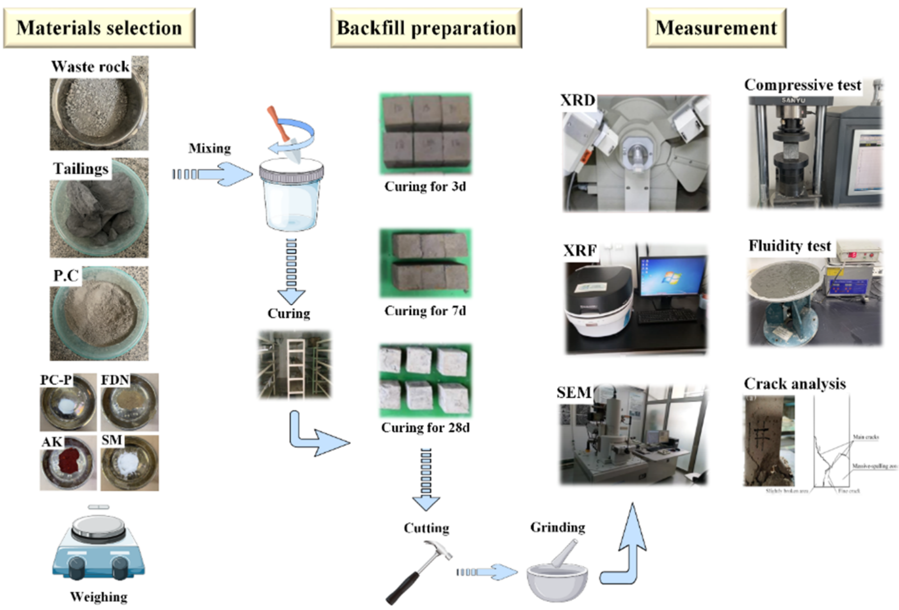

Figure 3 Experimental process and measurement methods

Table 3 Material proportioning scheme of the test specimens

Type	Portland cement/aggregate	Waste rock/tailings	Concentration (%)	Dosage (%)
PC-P	1:4	6:4	77%	$V_{P.C}$×0.15%
				$V_{P.C}$×0.25%
				$V_{P.C}$×0.35%
				$V_{P.C}$×0.45%
FDN	1:4	6:4	77%	$V_{P.C}$×0.40%
				$V_{P.C}$×0.60%
				$V_{P.C}$×0.80%
				$V_{P.C}$×1.00%
AK	1:4	6:4	77%	$V_{P.C}$×0.30%
				$V_{P.C}$×0.60%
				$V_{P.C}$×0.90%
				$V_{P.C}$×1.20%
SM	1:4	6:4	77%	$V_{P.C}$×0.30%
				$V_{P.C0}$×0.60%
				$V_{P.C}$×0.90%
				$V_{P.C}$×1.20%

2.2.2 Slurry fluidity test

According to GB/T 2419-2005 *Method for Determining the Fluidity of Cement Mortar*, the NLD-3 cement mortar fluidity meter was used to measure the fluidity of CPB-TW slurry (Geng et al. 2016), as shown in Figure 3. After pouring the slurry into test mould, the mould was vertically lifted and the jump table was activated, completing 25 jumps within 25 seconds. Finally, the bottom surface diameter of CPB-TW slurry and the diameter perpendicular to it were measured and averaged, which was the fluidity of the slurry.

2.2.3 Setting time test

The initial and final settings are closely related in terms of setting speed and time for cement and tailings, a variety of aggregates mixed to create the slurry. The initial setting is the length of time from the time water is added to the mixture until the slurry begins to lose its plasticity.

According to GB/T1346-2019 *Verification Method for Water Consumption of Standard Consistency, Setting Time, and Safety of Cement Paste* (Hou et al. 2024), a standard Vicat apparatus (Luda Instrument, China) was used to measure the backfill slurry setting time.

2.2.4 Scanning electron microscope test

The sample for SEM experiments is a thin section of 0.5 × 0.5 cm in size, and the sample should be able to reflect the colloidal state of the CPB. Metal spraying treatment is needed as the experimental sample is low in strength and poor in conductivity. After four minutes of gold spraying, the CPB samples reached the test conditions, and the prepared samples were subsequently tested for microstructure using SEM. Set the following parameters: working distance of 12–14 mm, resolution of 5 µm, and maximum acceleration voltage of 20 kV. In addition, it is crucial to note the distance and the optimal multiplier for adjusting the specimen to achieve the best experimental condition.

3 Results and discussion

3.1 Backfilling performance of CPB-TW with superplasticisers

The superplasticiser has its specific optimal dosage; thus the extensive exploration experiments are necessary to perform to obtain the backfilling superplasticiser suitable for Jinchuan nickel mine. It is acknowledged that the vibration slump range between 18 and 25 cm meets the demand for stable pipeline transportation of the CPB-TW slurry. As shown in Figure 4, the slump of CPB-TW was 21.75 cm, which can reach the fluidity standard of the paste. Comprehensively, with the increase of PC-P amount, the slump changes were not as significant as the other three superplasticisers. However, under the condition of 0.45% dosage, CPB-TW slurry with PC-P had the maximum slump of 25.1 cm among the superplasticisers selected in the experiments. It can be seen from Figure 4 that the dosage of superplasticiser and the slump presented a positive linear relationship. With the addition of 1.2% of the type of AK, the slump improved 29.2%, and the SM was 30.6%. When the addition amount exceeded the optimal dosage, the vibration slump of CPB-TW had a value that exceeded the transportation standard. The results showed that AK and SM superplasticiser had the best improvement effect on the fluidity of CPB-TW slurry. However, under the demand for stable pipeline transportation, the CPB-TW slurry with a 0.35% addition of PC-P had the best transportation performance.

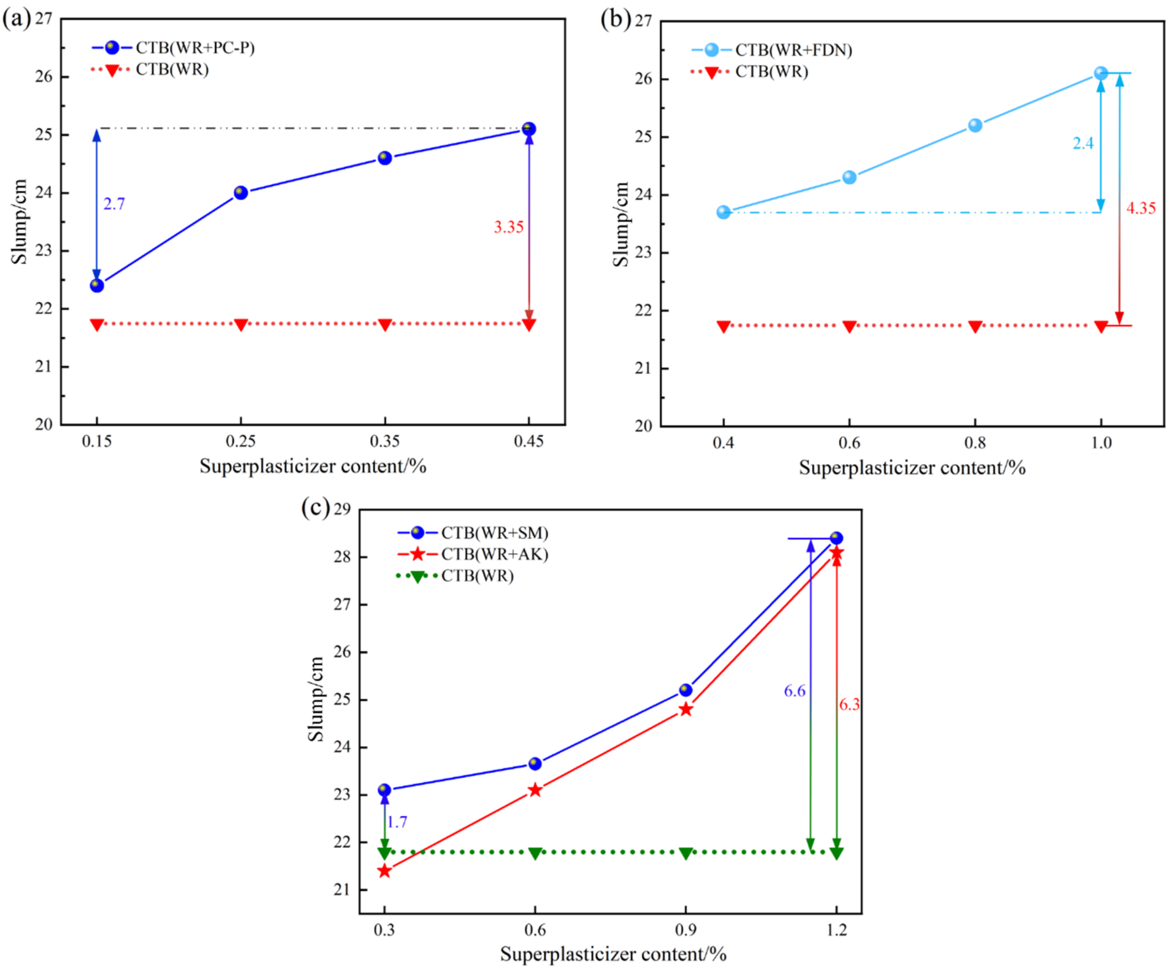

Figure 4 Slump of CPB-TW added with different dosage of superplasticisers

It can be seen from Figure 5 that the evolution of initial and final setting time for the CPB-TW specimens with various dosage gradients of four kinds of superplasticisers. The initial setting time of CPB-TW without superplasticiser was 308 min, and the final setting time is 1,239 min. When the dosage of PC-P was 0.15%, the initial setting time of the CPB-TW was reduced by 31 min, and the final time was reduced by 242 min (about 4 hours). However, the subsequent continuous increase of the addition amount results in the extension of the setting time. When the dosage of FDN and SM was between 0.4 and 1.2%, the evolution of initial and final setting time was basically the same, which had a large extent of shortening compared with the control group. The setting time began to increase when the dosage was more than 0.4%. Different from the evolution of the above three types of superplasticisers, there was a clear trend of decreasing in the initial and final setting time of the CPB-TW with the increase of AK superplasticiser.

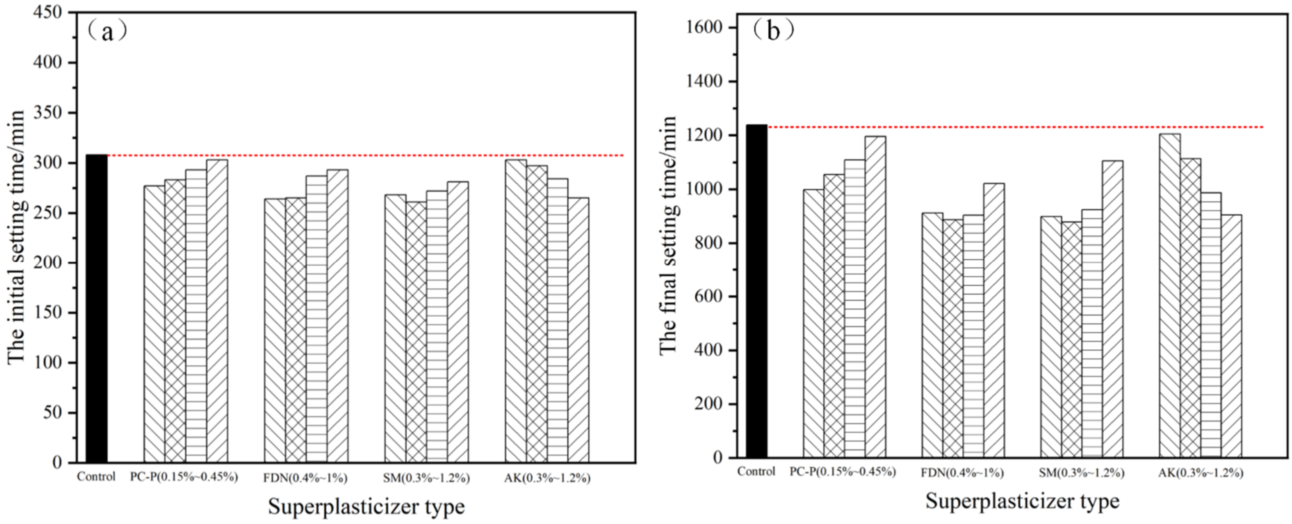

Figure 5 (a) Initial setting time and (b) final setting time of CPB-TW with four types of superplasticisers

3.2 Mechanical behaviours of CPB-TW with superplasticisers

When the dosage of PC-P was 0.35%, the UCS of CPB-TW reached its maximum value at 3, 7, and 28 days. However, compared with the group of 0.35% dosage, the UCS of CPB-TW added with 0.45% dosage of PC-P at 3, 7, and 28 days was decreased by 7.57, 2.95, and 2.02%, respectively. Besides, compared with the control group without superplasticisers, the CPB-TW sample adding PC-P had a significant increase in the UCS, as shown in Figure 6. It is obvious that the addition of PC-P had the greatest impact on the early UCS of CPB-TW and the optimal dosage was 0.35% (by mass of cements).

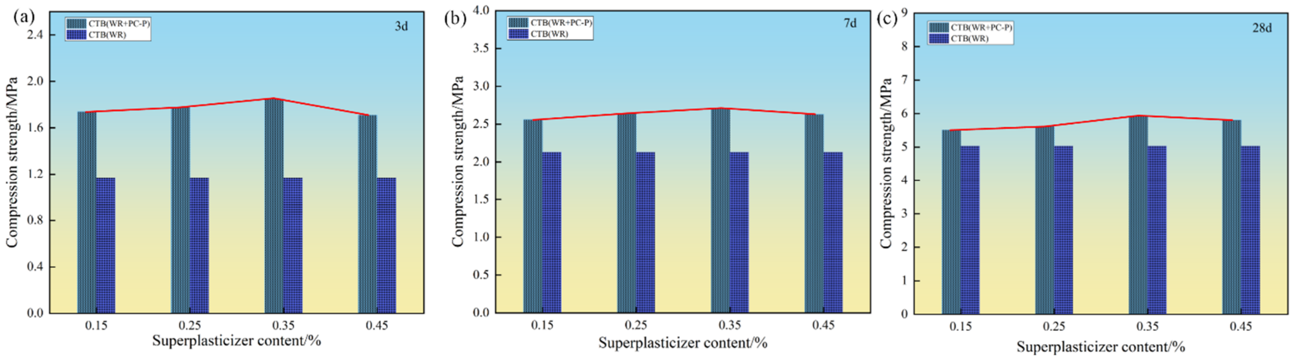

Figure 6 Relationship between cemented paste backfill (TW+PC-P) backfill strength and PC-P dosage

Figure 7 shows that FDN had a positive effect on the UCS at different curing ages. There was a linear correlation between the UCS and dosage. However, even though the dosage reached 0.4%, the gain effect was still not as good as the group with the addition of 0.45% PC-P type. Furthermore, compared with the control group without superplasticisers, the UCS of CPB-TW with maximum dosage of FDN at 3, 7, and 28 days was increased by 49.57, 37.09, and 15.5%, respectively.

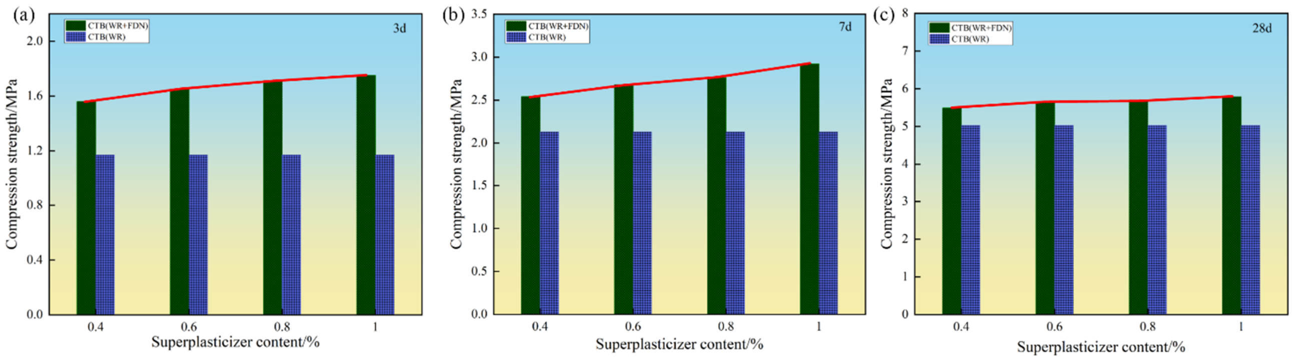

Figure 7 Relationship between cemented paste backfill (TW+FDN) backfill strength and FDN dosage

It can be seen from Figure 8 that the UCS of CPB-TW presented a change of first increasing and then decreasing as the dosage of AK and SM was increased from 0.3 to 1.2%. Moreover, when the dosage exceeded 0.9%, the UCS of CPB-TW-AK at 7 and 28 days continued to increase until the maximum value. However, compared with the group of 0.9% dosage, the UCS of CPB-TW added with 1.2% dosage of SM at 3, 7, and 28 days was decreased by 9.82, 6.18 and 2.5%, respectively. Different from the effect of AK, within the recommended dosage range by the manufacturer, there was a peak in the addition of SM. Thus, when selecting this superplasticiser, the appropriate dosage should be set according to the transportation requirements of Jinchuan nickel mine.

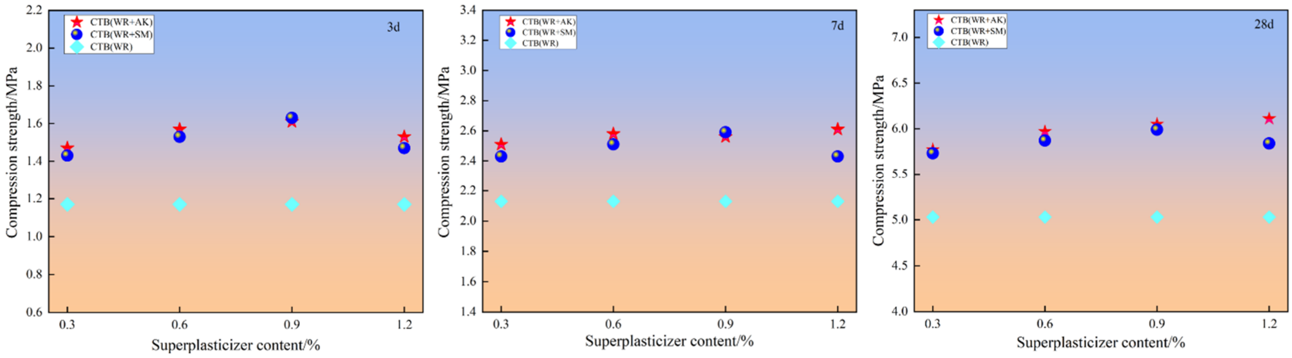

Figure 8 Relationship between cemented paste backfill (TW+AK/SM) backfill strength and AK/SM dosage

3.3 Microstructure analysis of CPB-TW

As can be seen from the experimental results, different types and dosages of superplasticisers can affect the quality of CPB-TW hydration products. In the CPB-TW consisted of tailings, WR, cement, and superplasticisers, the main linking effects of various materials were the products formed by the reaction of cement and water. Large amounts of stacked lamellar $Ca(OH)_2$ were generated in the CPB-TW slurry without superplasticiser, and a large number of clustered C-S-H connected with each other. Needle-shaped ettringite (AFt) was found in pores with larger sizes.

The tricalcium aluminate (C_3A), tricalcium silicate (C_3S), tetra calcium iron aluminate (C_4AF), and belite dicalcium silicate (β-C_2S) were the main components of the cement. Moreover, a calcium silicate hydrate gel (C-S-H) was generated by the reaction of C_3S and β-C_2S with water. Among them, C_3A had a higher reaction exotherm and a faster reaction rate, and the final product of C_3A hydration was related to the amount of gypsum incorporated. In the presence of sufficient $CaSO_4 \cdot 2H_2O$, AFt was generated. With the exhaustion of $CaSO_4 \cdot 2H_2O$, AFt continued to react with the unreacted C_3A and was converted into a monosulphate phase (AFm).

As can be seen from Figure 9, different superplasticisers had significant effects on the particle size of the C-S-H gel and the AFt crystal structure. According to the UCS test results, it can be found that the ettringite crystal structure had a greater influence on the CPB-TW strength. It can be seen from Figure 9b that AFt exhibited a narrow straw-like distribution structure after adding the FDN. Figure 9c shows that AFt exhibited a long needle-like structure after adding the SM. However, after the addition of PC-P and AK, AFt exhibited dense clusters of 'dandelion like' structures.

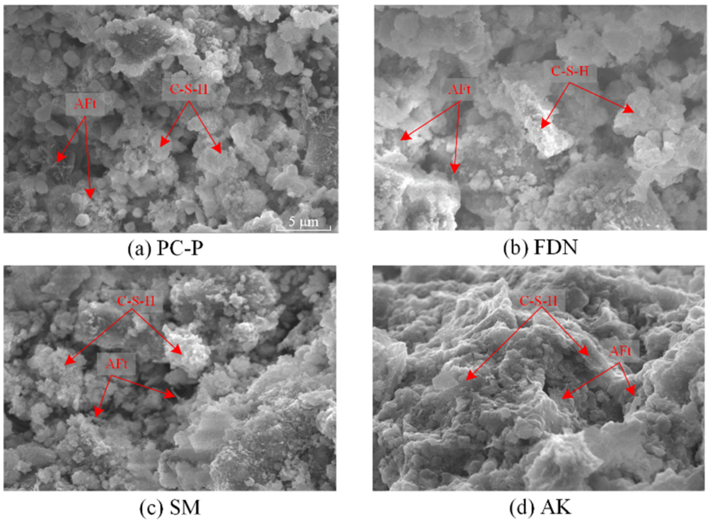

Figure 9 Morphology and microstructure of CPB-TW hydration products

3.4 Discussions

3.4.1 Effect of superplasticisers on the fluidity of CPB-TW slurry

In the CPB-TW with superplasticiser slurry, the fine particle components of tailings, cement, and WR were loosely interconnected and accumulated to flocculate with each other. Chemical bonds may have formed in some stacking areas, but most particles still flocculate with each other through physical connections. The addition of water reducing agents can break the flocculent structure in the slurry, release flocculent water, increase free water in the system, and improve the flow performance of the CPB-TW slurry.

It is acknowledged that the surface of cement particles carries Ca^{2+}, resulting in a positive Zeta potential. As shown in Figure 10, when the superplasticiser is added to the cements, such as the negative ions (-COO^-, -SO_3^- etc.) of PC-P will combine with Ca^{2+} on the cements surface to form an adsorption double layer, causing the Zeta potential on the outer surface of the cement particles to become negative. Under the action of electrical repulsion, the cement–water system is in a relatively stable state, making it difficult to form a flocculent structure. As a result, the fluidity of CPB-TW slurry can be effectively improved. Thus, with a fixed amount of cements, tailings, and WR, the amount of water used in the preparation of CPB-TW slurry can be reduced and the water reduction effect can be achieved.

Moreover, the macromolecules of superplasticisers contain a large number of hydrophilic polar groups, including sulfonic acid (-SO_3^-), hydroxyl (-OH), ether (-O-), amine (-NH_2), and carboxyl (-COO^-) groups. After the superplasticiser molecules are adsorbed on the surface of cement particles, and due to the hydrophilic effect of polar groups, a solvated water film with certain mechanical strength can be formed on the surface of cement particles. These hydration membranes can play a lubricating role, disrupt the flocculation structure in the CPB-TW slurry, release free water, and increase the workability of the mixture.

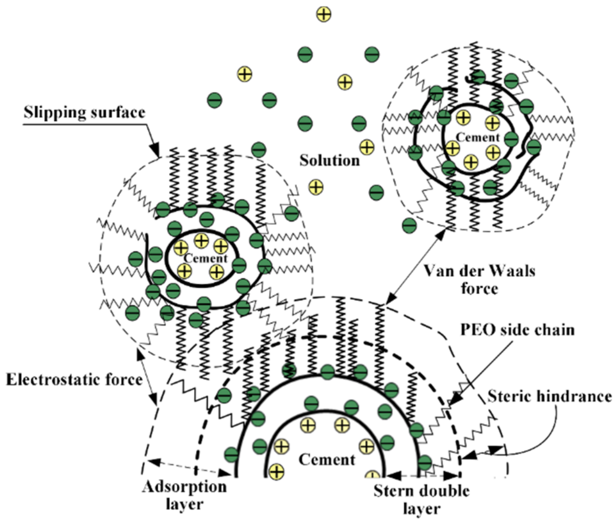

Figure 10 The steric hindrance effects of cement particles

3.4.2 *Effect of superplasticisers on the UCS of CPB-TW*

In the current cement concrete industry, in order to improve the inherent defects of cement-based materials or improve the performance of cement-based materials, various organic admixtures are usually added to the preparation process of cement concrete. The invention and application of superplasticisers are widely recognised as the third technological leap in the field of concrete technology after the technology of reinforced concrete and pre-stressed reinforced concrete. For the underground mines, the homogeneous and high concentration CPB slurry is usually filled into the mined-out area to form a backfill with certain mechanical strength to support the stability of the surrounding rock in the mined-out area.

Many researchers considered that after a relatively complete hydration product layer is formed in the cement particles, ions continue to hydrate through the hydration product layer, and the reaction rate is affected by the diffusion rate. As the hydration product layer thickens, the hydration reaction rate is completely controlled by the ion diffusion rate, and each product gradually grows closer. The macroscopic properties of concrete are as follows: needle shaped or rod-shaped AFt and other hydration products gradually overlap with each other, forming a preliminary three-dimensional network, and the concrete begins to lose its fluidity, resulting in a significant loss of slump. The formation of ettringite mainly involves the following steps:

$$AlO_2^{-}+2OH^{-}+2H_2O \rightarrow [Al(OH)_6]^{3-} \quad (1)$$

$$[Al(OH)_6]^{3-}+3Ca^{2+}+12H_2O \rightarrow [Ca_3Al(OH)_6 \cdot 12H_2O]^{3+} \quad (2)$$

$$2[Ca_3Al(OH)_6 \cdot 12H_2O]^{3+}+3SO_4^{2-}+2H_2O \rightarrow 2[Ca_3Al(OH)_6 \cdot 12H_2O] \cdot 3SO_4 \cdot 2H_2O \quad (3)$$

It can be seen from the above reaction equation that the formation process of AFt crystals mainly included three steps. The first step was the generation of octahedral $[Al(OH)_6]^{3-}$. Subsequently, the $[Ca_3Al(OH)_6 \cdot 12H_2O]^{3+}$ polyhedrons was formed by the meshing between the calcium polyhedrons and the $[Al(OH)6]^{3-}$. The internal charge of CPB-TW was finally balanced by the pillars. Furthermore, SO_4^{2-}, which can maintain the stability of AFt crystals, entered the previous pillars. It can also be found that the Na_2SO_4 content in the PC-P, the FDN, the AK, and the SM was 2.5, 5, 0.82, and 0.93 %, respectively. As a result, the content of SO_4^{2-} directly determined the number of stable AFt crystals generated after adding different superplasticisers.

Among the four types of superplasticisers selected in the experiment, PC-P type has excellent dispersion performance. On the one hand, the addition of PC-P increases the filling density of the cementitious material, and on the other hand, it releases more free water to participate in the cement hydration reaction, generating more $Ca(OH)_2$, promoting the reaction process. Thus, the early compressive strength of the CPB-TW can be greatly improved.

3.4.3 Superplasticisers comparison and optimisation

From the point of view of economic cost, the use of CPB-TW can reduce the cost of cementitious material use, optimise the particle size of C-S-H gel and ratio of the backfill material, increase the strength of the CPB, improve the flowability of the slurry, reduce the risk of pipe plugging, reduce the rate of pipe wear, and reduce drilling costs and pipe costs. By comparing the evolution of vibration slump and UCS of CPB-TW slurry added with four types of superplasticisers, it can be seen that the optimal dosage of PC-P type is relatively low. It means that the production costs can be reduced, and the UCS of CPB-TW added with PC-P can satisfy the production needs of Jinchuan nickel mine.

From the perspective of water reduction and dispersion mechanism, the superplasticisers most related to the effect of electrostatic repulsion in turn were the ionic polymers with sulfonic acid ions, polymers with carboxylic acid ions, and non-ionic surface-active superplasticiser with hydroxyl and ether groups. There is no doubt that PC-P type has the best dispersion performance for cement particles. Furthermore, under the dosage of 0.35%, the final UCS of CPB-TW added with PC-P, FDN, AK, SM is increased by 17.9, 9.1, 15.5, and 15.3%, respectively. According to the above findings, PC-P superplasticiser exhibited the optimal enhancement effects on the mechanical behaviours and backfilling performance of CPB-TW. In conclusion, PC-P type shows obvious characteristics of ;low dosage and high improvement;.

4 Conclusion

The purpose of this study is to select the optimal superplasticiser suitable for Jinchuan nickel mine that has a strengthening effect on the UCS and flow performance of CPB-TW. Therefore, an experimental investigation of the mechanical behaviours and backfilling performance of CPB-TW was conducted by adding different superplasticisers with various dosage gradients. The following primary conclusions can be derived from the experimental findings of this study:

1. The four optimal dosages of superplasticisers investigated in the experiment are as follows: PC-P×0.35%, FDN×0.6%, AK×0.9%, SM×0.6% (by mass of cements), all of the groups satisfied the requirements for pipeline transportation in Jinchuan nickel mine, and there was no deterioration effect on the backfill strength at 3, 7, and 28 days.
2. In the setting range of high dosage, AK and SM superplasticisers had the best improvement on the fluidity of CPB-TW slurry. In contrast, PC-P superplasticiser exhibited the optimal enhancement effects on the mechanical behaviours and backfilling performance of CPB-TW at low dosage.
3. Under the dosage of 0.45%, the final setting time of the CPB-TW slurry added with PC-P, FDN, and SM superplasticiser was significantly reduced by 3.5, 26.4, and 28.6%, respectively. However, the subsequent continuous increase of the AK dosage resulted in the extension of the setting time.
4. Different superplasticisers had different effects on the microstructure of the CPB-TW, which was mainly manifested in the changes in the particle size of the C-S-H gel and the AFt crystal structure. Without superplasticiser, the AFt exits as unregular rod shape and small size. When adding superplasticiser, the size of ettringite increased to 3~5 µm. The shape and size of ettringite and the connection form between ettringite and the C-S-H gel are correlative to the UCS of the CPB-TW sample.
5. To achieve efficient and low-cost production in Jinchuan nickel mine, it is most suitable to use PC-P superplasticiser as the admixture for CPB-TW slurry pipeline transportation.

In this paper, after extensive experimental research, it was found that the CPB-TW slurry concentration of 77 and 60% of WR can be better used in mine backfill projects. Moreover, CPB-TW with PC-P (cement content ×0.35%) had the optimal backfilling performance indicators. However, the only coarse aggregates selected in this paper are WR, and new coarse aggregates can be developed for mine backfill projects in future studies.

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