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Original Article

New advances in *in-situ* simulation test technology for cemented paste backfill and its mechanical response characteristics

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ABSTRACT

In-situ mining environmental factors, including temperature, pressure, and pore water pressure, significantly alter the curing process of cemented tailings backfill. This leads to pronounced discrepancies in mechanical properties between laboratory specimens prepared with identical mix ratio and core samples extracted from mining stopes. Accurate prediction of the mechanical properties of cemented paste backfill (CPB) under *in-situ* conditions is a critical prerequisite for achieving economically optimal design of backfill mix proportions in mining operations. While substantial research has been conducted globally on the influence of individual environmental factors on tailings backfill properties, quantitative studies addressing the coupled effects of multiple environmental factors remain relatively scarce. This paper systematically reviews the current state of research on the mechanical properties of tailings cemented backfill under *in-situ* conditions in mining areas. Focusing on three core *in-situ* environmental factors—curing pressure, curing temperature, and pore water pressure—it analyzes their influence mechanisms on backfill strength and summarizes the application characteristics and limitations of existing backfill curing devices. On this basis, the paper introduces the *in-situ* environmental physical twin testing apparatus for mine backfill developed by the BGRIMM Technology Group. This apparatus precisely simulates the curing conditions of the actual mining environment in a laboratory setting, i.e., temperature, pressure, and pore water pressure. It enables quantitative research on the effects of multiple *in-situ* environmental factors on the mechanical properties of CPB, providing critical experimental support for optimizing mine backfill mix designs.

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1 Introduction

Backfill mining has emerged as a core technology for green mining in metal mines, owing to its significant advantages in ensuring safe mining operations, improving stope recovery rates, and realizing resourceful disposal of mining solid waste [1–3]. However, in practical engineering applications, the mechanical properties of *in-situ* cemented tailings backfill in mining stopes differ substantially from those of laboratory-prepared backfill specimens with the same material ratios. This discrepancy arises because the laboratory curing environment cannot replicate the multi-field coupled conditions—such as temperature, pressure, and pore water pressure—present in the mining stopes [4, 5].

On one hand, earlier fill materials in the mine undergo compression curing under the gravitational load of subsequent backfill placement, which further compacts the skeletal structure of the fill body. Consequently, its *in-situ* strength can be 3–4 times higher than that of laboratory specimens with the same mix design [6]. On the other hand, the underground mining environment is influenced by both geothermal effects and the hydration heat release of cementitious materials, resulting in temperatures significantly higher than standard laboratory curing conditions. The thermal stresses generated by high temperatures readily induce the development of microcracks within the backfill, leading to strength degradation.

At present, the design of mine backfill mix proportions still mainly relies on mechanical strength test results of laboratory standard-cured specimens [7], failing to fully consider the regulatory effect of *in-situ* mining environment factors on the mechanical properties. This makes it difficult to determine mix proportions that match the actual *in-situ* engineering requirements, often leading to excessive addition of cementitious materials and a significant increase in the economic cost of mine backfilling operations [8, 9].

In recent years, interdisciplinary integration of geotechnical engineering, mining engineering, and experimental testing technologies has driven considerable progress in research on the mechanical properties of cemented tailings backfill under *in-situ* conditions, with innovative experimental methods and testing technologies emerging continuously. In light of this, this paper systematically reviews the domestic and international research on the mechanical properties of cemented paste backfill (CPB) under *in-situ* stope conditions. It analyzes the influence laws of three core *in-situ* environmental factors—curing pressure, curing temperature, and pore water pressure—and the development status of backfill curing devices. By examining the advantages and limitations of existing testing apparatus, this study aims to provide reference and guidance for future research in this field, and to facilitate the design of mine backfill mixtures that better reflect practical engineering conditions while maintaining economic feasibility.

2 Influencing factors on mechanical properties of cemented paste backfill

Compared with the standard laboratory curing environment, the *in-situ* conditions of the mine stope have significant discrepancies in pressure, temperature, humidity, drainage conditions, and other aspects, and these discrepancies have a marked impact on the mechanical properties of cemented paste backfill. Existing experimental studies in China and abroad have confirmed that the mechanical properties of backfill specimens prepared by the standard laboratory curing method are significantly different from those of *in-situ* cored backfill specimens with the same mix proportion [10, 11].

2.1 Effect of curing pressure

Extensive investigations have been conducted worldwide on the effect of curing pressure on the strength of CPB, which can be broadly divided into two main research streams. The first stream focuses on the effect of slurry self-weight stress by adjusting the casting height of CPB specimens, while the second stream involves the development of dedicated pressurized curing apparatus to explore the action mechanism of external loads.

Belem et al. [6] conducted high square column model tests and revealed that the self-weight consolidation and drainage process of fresh CTB slurry predominantly occurred within the first 72 h of curing, and that optimized drainage conditions can significantly promote the strength gain of CTB. Béket Dalcé et al. [12] performed tests using moulds with varying heights, and confirmed that self-weight stress exerted a negligible effect on CTB strength at low slurry heights, whereas segregation dominated at large casting heights. Specifically, the upward migration of cement particles results in a markedly higher strength in the upper section of the backfill compared to the bottom section.

With respect to pressurized curing research, Benzaazoua et al. [13] and Yilmaz et al. [16] developed a pneumatically controlled pressurized curing system for CPB, enabling accurate simulation of the *in-situ* stress environment of underground mine stopes. Based on this apparatus, systematic investigations by Yilmaz et al. [14–16] demonstrated that pressurized curing can effectively reduce the porosity and enhance the strength of CPB. Furthermore, the strength enhancement effect induced by curing pressure is mainly concentrated in the early curing stage, and gradually decreases with increasing curing age. It was also identified that the strength of specimens cured under bottom drainage conditions had the best agreement with the mechanical properties of field-cored CPB samples. Subsequently, Zhao et al. [17] further clarified the strength enhancement mechanism of pressurized curing using a self-developed pressurized curing apparatus. They found that the application of pressure in the early curing stage achieved slurry compaction, increased inter-particle contact area, reduced pore water pressure to accelerate the hydration of cementitious materials, and thus optimized the microscopic compactness of CPB. In addition, the developed apparatus enables the control of multi-dimensional test conditions, including lateral stress, confining pressure, and temperature–pressure coupling, as well as real-time monitoring of key test parameters.

Overall, existing investigations worldwide have verified that pressurized curing can improve the mechanical properties of CPB by optimizing its microstructure, accelerating slurry drainage, and facilitating the hydration of cementitious materials. Furthermore, this strength gain effect exhibits a pronounced time-dependent behavior, which is predominantly exerted in the early curing stage and gradually weakens with increasing curing age.

2.2 Effect of curing temperature

CPB specimens prepared in the laboratory are conventionally cured in a constant-temperature curing chamber. Nevertheless, the *in-situ* temperature of underground mine stopes is highly dynamic and heterogeneous, which differs remarkably from standard laboratory curing conditions, due to the combined effects of geothermal gradient, exothermic hydration of cementitious materials in backfill slurry, and complex underground mining conditions.

With the mining industry in China entering the deep mining era, the mining depth of most mines has commonly exceeded 1000 m, with working face temperatures reaching up to 40 °C. In other countries worldwide, some mines have achieved mining depths of 2000 to 3000 m, and the Anglogold Gold Mine even reaches a mining depth of 3800 m [18]. Field monitoring data have demonstrated that surrounding rock temperature rises linearly with increasing mining depth, and can reach as high as 70 °C at a depth of 5000 m.

To date, extensive investigations have been conducted worldwide on the effect of curing temperature on the mechanical properties of CPB, with many fruitful results achieved. Bresson et al. [19] confirmed that curing temperature exerted a pronounced influence on the microstructure and mechanical behavior of CPB, and that high-temperature curing conditions facilitated the formation of a more stable internal microstructure within CPB. Elkhadiri et al. [20] investigated the performance evolution of CPB cured at temperatures ranging from 4 to 85 °C, and revealed that elevated temperatures can accelerate the hydration kinetics of cementitious materials and enhance the early-age strength of CPB. However, excessively high curing temperatures induce an increase in porosity and heterogeneous microstructure of CPB, which further leads to a reduction in its long-term strength.

Aldhafeeri et al. [21] identified through laboratory tests that the impact of curing temperature on CPB strength was mainly concentrated in the early curing stage, and gradually decreased with increasing curing age. Liu et al. [22] compared five different curing regimes, and found that CPB cured in a 35 °C constant-humidity water bath exhibited higher strength than those cured under the other four regimes. They

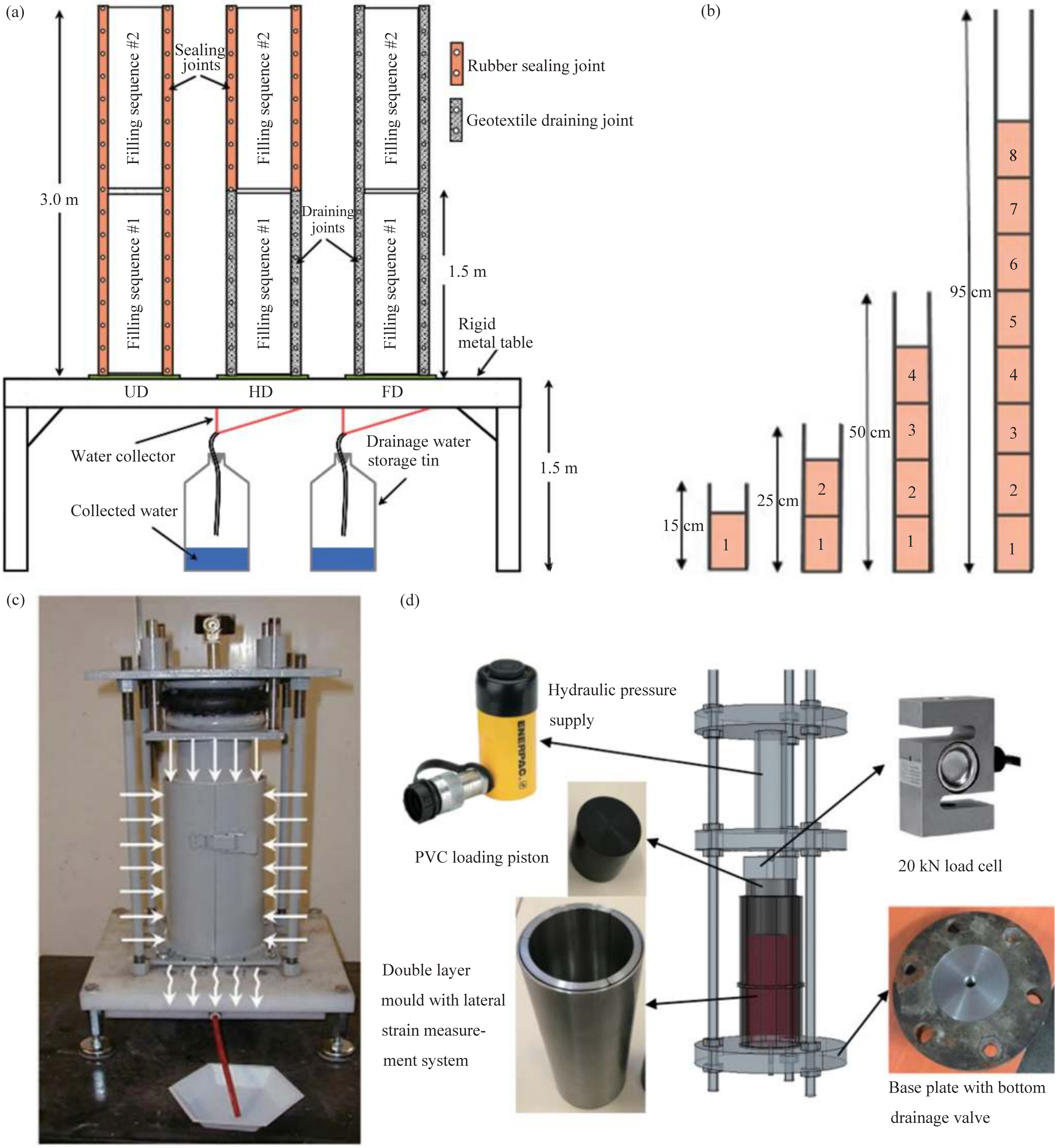

Figure 1 Test equipment for the influence of curing pressure on CPB strength. (a) CPB strength test apparatus (drainage & self-weight stress) [6]; CPB strength test (self-weight stress & segregation) [12]; (c) Benzaazoua's CPB pressurized curing apparatus [13]; (d) Zhao's lateral strain measurable curing apparatus [17]

also noted that temperature elevation can substantially improve the early-age strength of CPB by promoting the early hydration reaction of cementitious materials. Fall et al. [23] performed a series of tests under various high-temperature conditions, and found that increasing curing temperature can enhance CPB strength when the curing temperature was below 200 °C, while the strength decreased drastically with rising temperature once the curing temperature exceeded 200 °C. Furthermore, they clarified that the sensitivity of

CPB mechanical properties to curing temperature was closely related to the cement-to-tailings ratio and mineralogical composition of the tailings. Overall, the aforementioned studies consistently demonstrate that curing temperature affects the mechanical properties of CPB primarily by regulating the hydration degree of cementitious materials in fresh backfill slurry. This regulatory effect mainly occurs in the early consolidation stage of the slurry, and weakens gradually as the hydration reaction proceeds. An appropriate curing temperature can effectively improve the strength of CPB. In contrast, excessively low temperatures inhibit the hydration reaction of cementitious materials, while excessively high temperatures generate microcracks inside CPB due to thermal stress, both of which are detrimental to the strength development of CPB.

2.3 Effect of pore water pressure

During the consolidation process of CPB slurry, pore water pressure is generated under the combined effects of self-weight stress, external loads and other factors. This pressure acts on the internal particles and pore structure of CPB, and further exerts a critical impact on its mechanical properties. The pore water pressure in CPB is mainly derived from two sources: the seepage field induced by the self-weight of pore water, and the variation of total stress acting on the CPB skeleton.

Ghirian et al. [24] investigated the effect of thermo-hydro-mechanical-chemical (THMC) multi-field coupling mechanism on the performance of CPB, and revealed that the evolution of pore water pressure during consolidation was dominated by the hydration degree of cementitious materials, segregation, water evaporation, and the self-weight of CPB. The dynamic change of pore water pressure further induced the variation of internal porosity and the initiation and propagation of microcracks within CPB specimens, which ultimately dominates the mechanical properties of the cured CPB. When studying the influence of self-weight stress on the mechanical behavior of CPB, Béket Dalcé et al. [12] found that under undrained conditions at the bottom during slurry consolidation, the upward seepage induced by segregation transported fine cement particles to the upper section of the slurry, thus increasing the cement content and corresponding strength of the upper part of the CPB specimen. This finding verified that upward seepage would lead to significant heterogeneity in the strength distribution of CPB. Zhou [25] conducted a series of centrifuge tests with varying rotational speeds to simulate the *in-situ* seepage conditions in underground stopes, and systematically studied the influence of

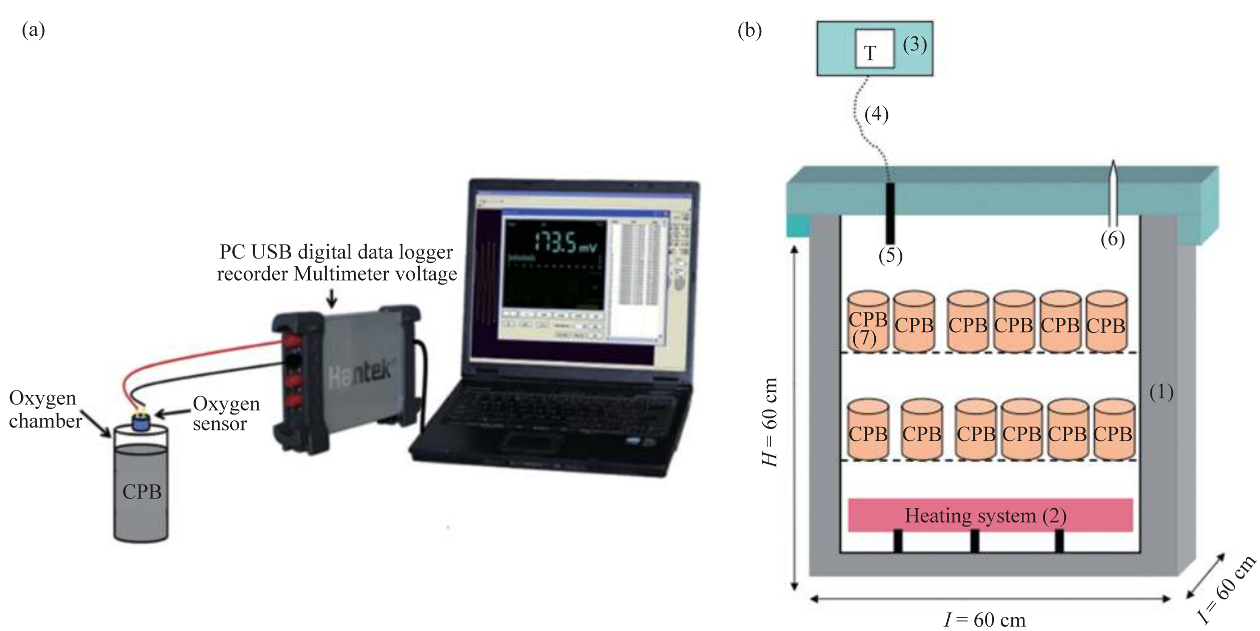

Figure 2 Test equipment for the influence of curing temperature on CPB strength. (a) Diagram of oxygen consumption test device for CPB specimens [21]. (b) CPB specimens subjected to curing in an electric furnace [23]

different seepage water pressures on the mechanical properties of CPB. Their results demonstrated that the compressive strength of CPB specimens decreased continuously with increasing seepage force; the elastic modulus exhibited an initial increase followed by a subsequent decrease, and the peak strain presented an overall downward trend.

Existing investigations on the influence of pore water pressure on the mechanical properties of CPB mainly focus on the effect of seepage field induced by the self-weight of pore water, while neglecting the variation of pore water pressure caused by key factors including drainage conditions. Furthermore, most current studies on the mechanical properties of CPB under *in-situ* stope environments mainly take curing temperature and curing pressure as the core influencing factors, and there is a distinct research gap in systematic investigations that treat pore water pressure as an independent and controllable influencing variable.

3 Research progress on backfill curing devices

To make laboratory-prepared CPB specimens more representative, researchers in China and abroad have developed a variety of CPB curing devices. The reproduction and control of environmental factors of these devices have important reference value for the development of the cemented backfill twin experimental device in this project.

The weight pressurized curing device designed by Belem et al. [26] can explore the influence of pressure, but its pressure control is inaccurate with a narrow range, which cannot simulate the actual compression conditions of the stope. The CUAPS pneumatic pressurized curing device developed by Benzaazoua et al. [13] solves the problem of accurate pressure control, and allows internal observation and investigation of the influence of different drainage positions. Yilmaz et al. [27] improved this device by adding permeable stones and various sensors to monitor pressure, deformation and pore water pressure. The multi-field curing test device designed by Chen Shunman et al. [28] can control pressure, temperature and humidity and monitor relevant parameters, and can simulate the pressure and temperature of the stope, but it only has bottom drainage and no seepage water pressure control system. The multifunctional test device developed by Qu et al. [29] can quantitatively control temperature and pressure, improve the preparation efficiency of specimens, and apply pressure in different directions to simulate complex stress conditions.

However, most existing devices focus on the influence of temperature and pressure, generally lack a pore water pressure control system, and cannot carry out quantitative research on its influence. To reproduce the curing conditions of the *in-situ* stope environment in

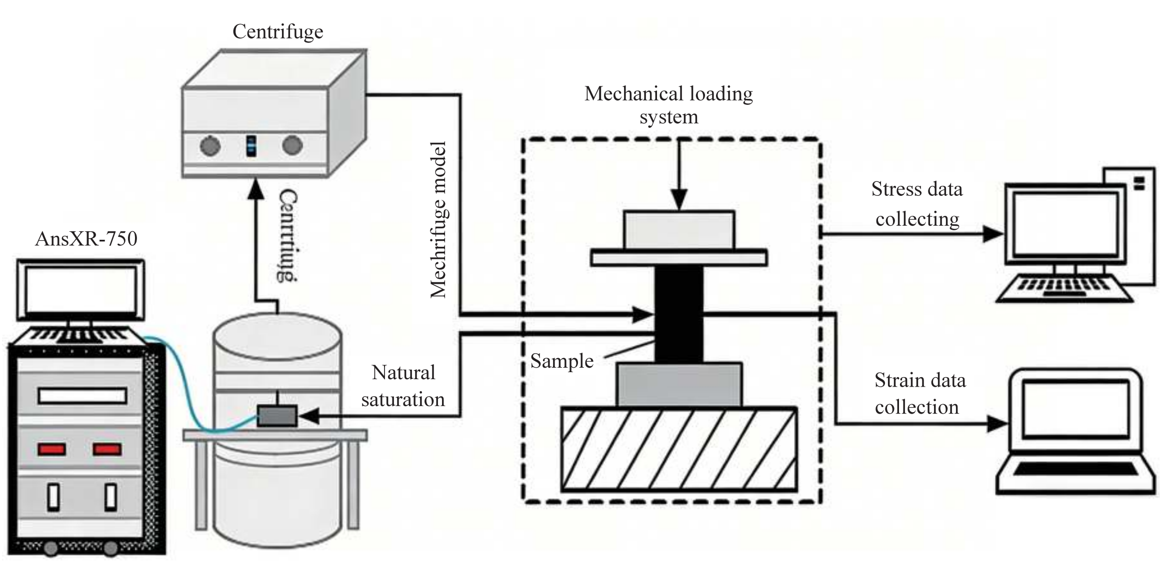

Figure 3 Test device for the influence of seepage water pressure on the mechanical properties of backfill [25]

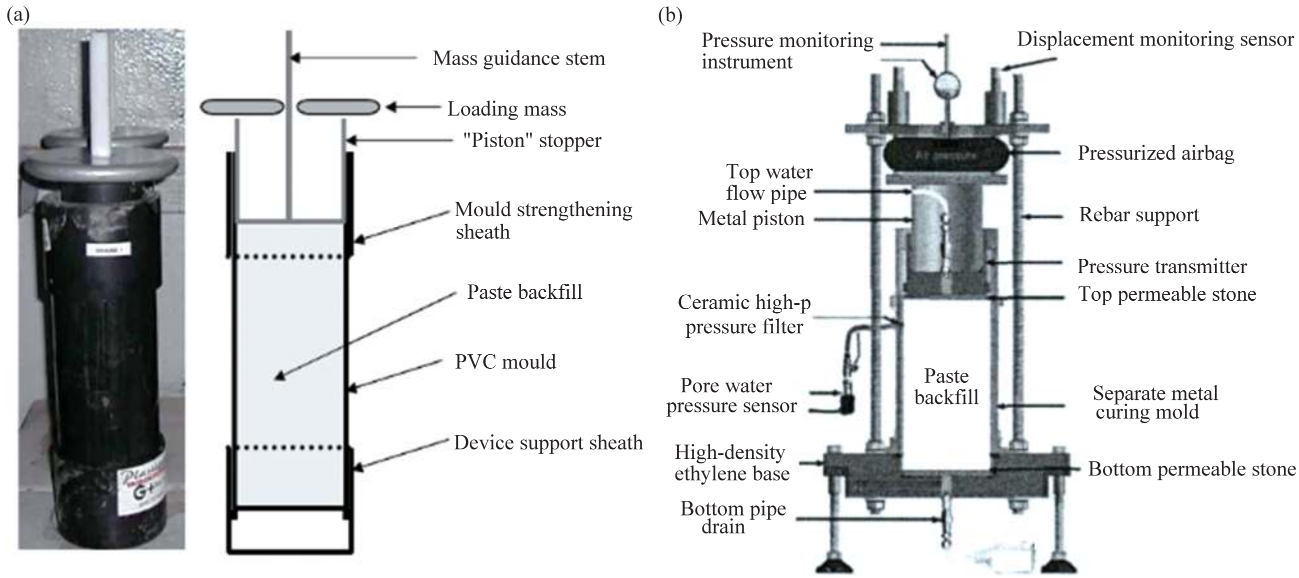

Figure 4 Development of curing devices. (a) CPB curing apparatus developed by Belem [47]. (b) Modified CUAPS curing apparatus [48]

the laboratory and make the laboratory-prepared CPB specimens more representative, researchers in China and abroad have developed a large number of CPB curing devices. The reproduction and control methods of various environmental factors in these curing devices have important reference value for the fabrication of the cemented backfill twin experimental device in this project.

4 Investigation on the effect of *in-situ* stope environment on the mechanical behavior of CPB

Through a comprehensive review of published literature, it is found that existing investigations on the influence of *in-situ* stope environment on the mechanical properties of CPB are mostly limited to qualitative analysis of single or dual factors, while systematic quantitative research on multi-factor coupling effects remains insufficient. Furthermore, most existing CPB curing apparatuses are mainly designed for pressurized curing, with temperature control relying on conventional constant-temperature curing chambers. They are generally not equipped with an independent pore water pressure control module. These limitations make it impossible to replicate the *in-situ* stope environment accurately, and the test results obtained from such apparatuses cannot reliably predict the *in-situ* strength of field backfill. To address these research gaps, the authors developed a novel physical field-twin test apparatus for the *in-situ* stope environment of CPB [30]. This apparatus enables synchronous or independent regulation of curing pressure, curing temperature, and pore water pressure, allowing for systematic quantitative investigation of the independent and coupling effects of these environmental factors on CPB mechanical properties. The research outcomes of this apparatus can provide theoretical and technical support for mines to optimize the backfill mix proportion according to the actual *in-situ* stope environment.

4.1 Design of a physical field-twin test apparatus for in-situ stope environment

This test device includes a stability control module, an external stress control module, a pore water pressure control module, and a temperature control module. By adjusting the parameters of each module, the actual conditions of the *in-situ* filling stope can be simulated. Furthermore, a cemented filling body that is twin to the *in-situ* conditions of the deep stope is prepared and cured. Further physical and mechanical property tests of the corresponding filling slurry or filling body are carried out to grasp the *in-situ* strength characteristics of the actual stope filling body. This device can adjust the pressure, drainage conditions, and ambient temperature as needed to simulate the *in-situ* environment of the stope. Based on the pressure, drainage conditions and temperature of the actual filling environment in the mine, after preparing the *in-situ* environmental filling body specimens of the stope, the mechanical properties of the filling specimens after curing can be tested to verify whether the filling body meets the mining strength and relevant process requirements, to determine the proportion and control parameters of the filling materials in the goaf of the stope.

4.2 Application of in-situ environment physical twin test apparatus

Based on the self-developed physical field-twin test apparatus for replicating the *in-situ* stope environment of mine CPB, a series of systematic laboratory tests were performed. The uniaxial compressive strength (UCS) and microstructure characteristics of CPB specimens under varying combinations of curing temperature, curing pressure, and pore water pressure were systematically characterized, and the evolution law of CPB mechanical properties affected by *in-situ* stope environmental factors was comprehensively elucidated.

4.2.1 Experiment preparation

4.2.1.1 Tailings

The tailings used in this study originated from a certain mine in Xizang. Among them, after the tailings were dried at high temperature (105±3 °C), their specific gravity was measured to be 2.919. Figure 1 shows the tailings particle size distribution data obtained by the laser particle size analyzer. The results show that the characteristic particle sizes d_{10}, d_{30}, and d_{60} are 2.653, 11.679, and 50.432 μm, respectively. The calculated unevenness coefficient C_u is 19.00 and the curvature coefficient C_c is 1.02, indicating that the particle size distribution of the entire tailings in the Karatongke copper-nickel mine is wide, meeting the conditions of $C_u > 3$ and $C_c = 1–3$, suggesting that the gradation of the tailings is good and continuous. X-ray fluorescence (XRF) determination was conducted on the tailings, and the results are shown in Table 1. It can be seen that the main metallic elements contained in the tailings are Fe, Al, Mg, and Si, and the content of the non-metallic element S is 1.9%.

4.2.1.2 Binder and water

Ordinary Portland cement (P.O 32.5), which is commonly used in mines, was chosen as the binder for this experiment. In addition, local tap water was used to prepare the samples.

The test scheme is shown in Table 2.

4.2.2 Effect of curing pressure on the UCS of CPB

As shown in Figure 7, in the strength development process of CPB, increasing the curing pressure is conducive to improving the mechanical properties of cemented paste backfill. There is a positive correlation between curing pressure and the uniaxial compressive strength of cemented paste backfill. The uniaxial compressive strength of cemented paste backfill increases with the rise of curing pressure, while the increasing

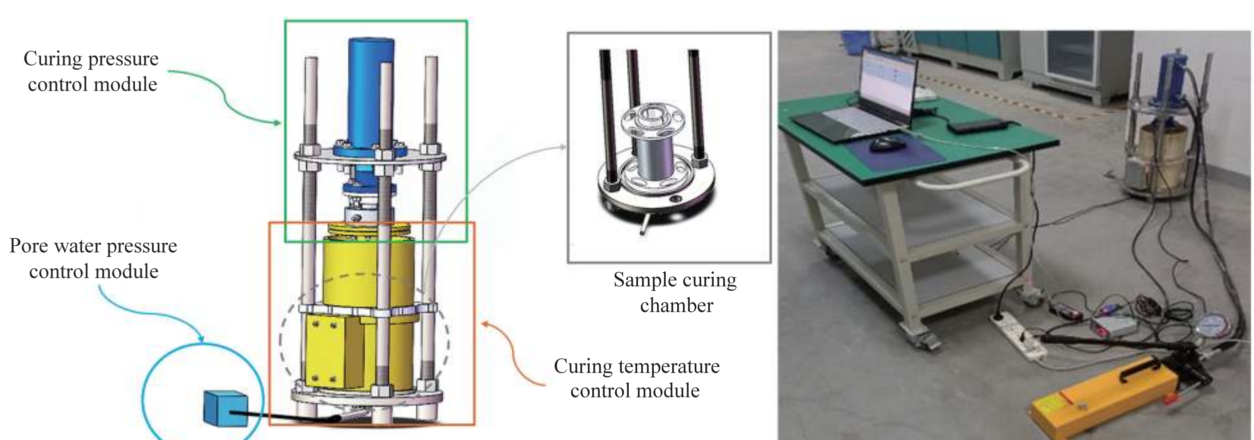

Figure 5 The test device for simulating the *in-situ* curing environment of cemented filling bodies

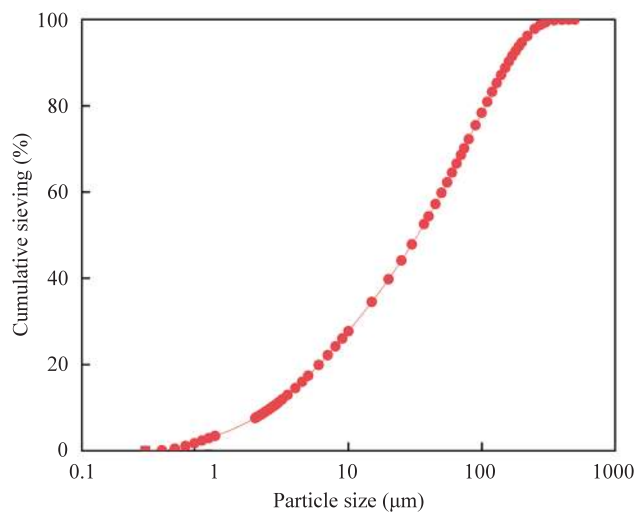

Figure 6 The particle size distribution curve of the backfill aggregate

Table 1 The chemical composition of the backfill aggregate

Element	Ca	Si	Al	Mg	Fe	Mn	Ti
Content (%)	3.69	20.37	6.39	8.21	12.09	0.14	0.45
Element	P	K	Na	S	C		
Content (%)	0.13	0.85	1.83	1.9	0.35		

Table 2 Influencing factors and levels

Curing temperature (°C)	Pore water pressure (kPa)	Curing pressure (kPa)
35	50	0, 250, 500, 750
45	50	0, 250, 500, 750
55	50	0, 250, 500, 750
45	0, 50, 100, 150	750

trend decreases continuously.

The reasons for the effect of curing pressure on the mechanical properties of CPB can be summarized as follows:

i) At the stage before the cemented backfill slurry is consolidated, curing pressure accelerates the cement hydration reaction and produces more cement hydration products. After the filling slurry is consolidated, the pores between tailings particles are compacted by curing pressure, and the number of pores is reduced, which helps the cement hydration products form a stable structure between the particles.

ii) The excess pore water inside the slurry is discharged by curing pressure, which reduces the water–cement ratio of the slurry and further promotes the cement hydration reaction.

4.2.3 Effect of curing temperature on the UCS of CPB

As illustrated in Figure 8, curing temperature exerts a pronounced influence on the mechanical properties of CPB. During the curing process of CPB, the UCS of CPB specimens exhibits an initial increase followed by a subsequent decrease with rising curing temperature, indicating the existence of an optimal curing temperature corresponding to the maximum UCS of CPB. The underlying mechanisms of this phenomenon are elaborated as follows:

i) The hydration reaction of cementitious materials requires an appropriate reaction temperature, which varies for different CPB specimens due to the

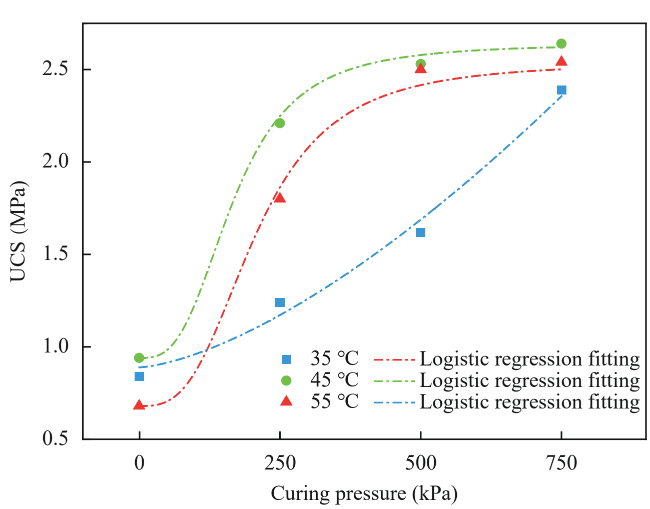

Figure 7 The effect of curing pressure on the uniaxial compressive strength of backfill specimens

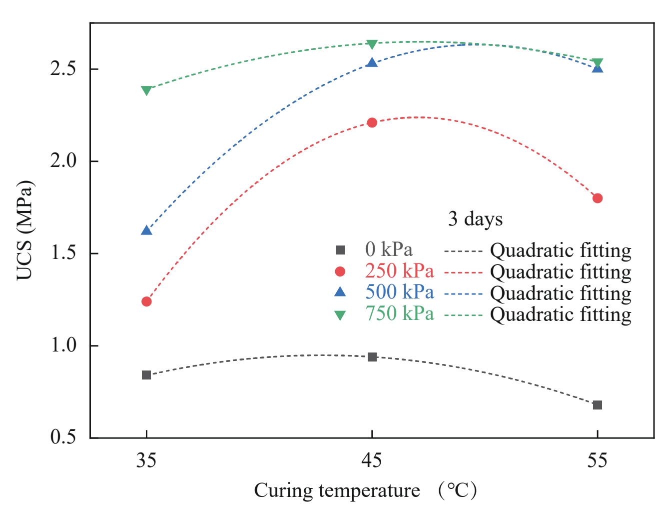

Figure 8 The effect of curing temperature on the uniaxial compressive strength of backfill specimens

combined effects of backfill slurry mix proportion, curing pressure, and other test parameters. In this study, the optimal temperature range for cementitious hydration of all specimens is determined to be 40–50 °C. At the early curing stage of CPB, when the curing temperature is within this optimal range, the hydration reaction of cementitious materials proceeds more sufficiently, which accelerates the cementation process of the fresh slurry and thus enhances the strength of the cured CPB. As curing progresses, the hydration reaction of cementitious materials gradually stagnates with the continuous consumption of reactants, leading to a diminished effect of hydration on the mechanical properties of CPB specimens.

ii) In addition to regulating the hydration reaction of cementitious materials, curing temperature also has a critical impact on the evolution of internal pores and cracks within CPB specimens. When the curing temperature reaches 55 °C, the high ambient temperature induces a temperature rise of the pore air and pore fluid inside the specimens, which further generates a thermal expansion effect on the internal pore structure of CPB. The resulting expansion stress drives the expansion of micro-pores within the specimens, alters the pore size distribution of CPB, and ultimately leads to a reduction in the mechanical strength of the specimens.

4.2.4 Effect of pore water pressure on the UCS of CPB

As shown in Figure 9, pore water pressure leads to the strength deterioration of CPB. Under the same conditions of curing temperature and curing pressure, there is a negative correlation between the uniaxial compressive strength of cemented paste backfill and pore water pressure. The strength of the backfill decreases with the increase of pore water pressure, and the decline amplitude increases with the rise of pore water pressure.

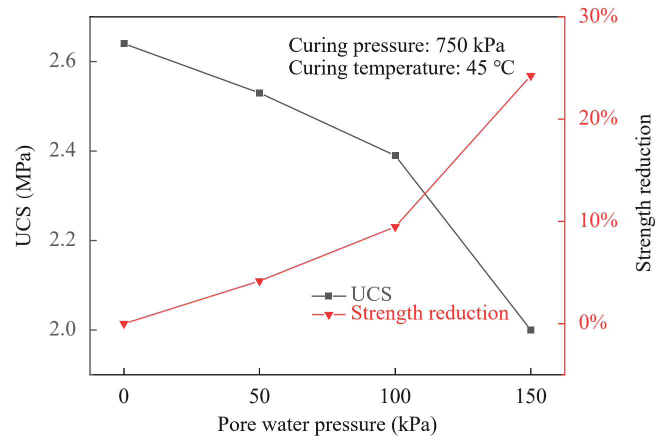

Figure 9 The effect of pore water pressure on the uniaxial compressive strength of backfill specimens

4.3 Microscopic behavior analysis

4.3.1 SEM results under standard curing

During the hydration reaction of Portland cement, the main products are calcium silicate hydrate (C-S-H gel), calcium hydroxide (CH), as well as calcium aluminate hydrate or calcium sulfoaluminate hydrate. Among them, C-S-H gel accounts for the highest proportion in the hydration products, and has the most significant influence on the mechanical properties of cemented paste backfill (CPB). C-S-H gel has a porous structure, which is fibrous and distributed among particles such as tailings aggregate, binding the internal particles of the backfill into a whole. Figure 10 shows the scanning electron microscope images of standard curing specimens with a curing age of 3 days under different magnifications. From Figure 10(a) to 10(b), it can be found that the cemented paste backfill is composed of numerous fine particles, and the particle surfaces are covered with fibrous C-S-H gel. With further magnification, from Figure 10(c) to 10(d), it can be found that the fibrous C-S-H gel on the particle surface is densely distributed, cross-connected with each other, and tightly bonds adjacent particles, realizing the mutual fixation between particles and making them form an

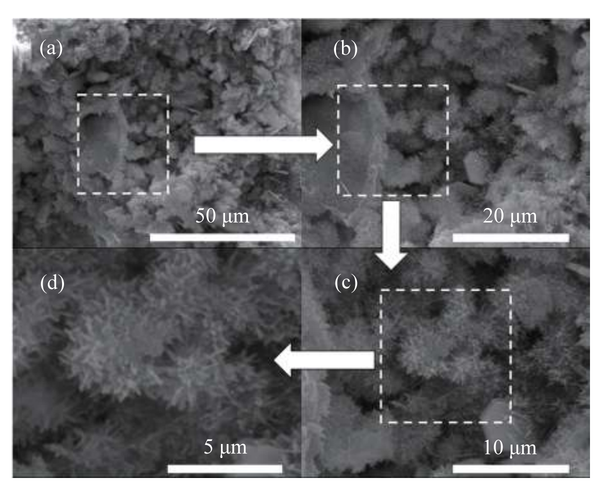

Figure 10 SEM images of standard curing specimens (curing age: 3 days)

integral whole.

4.3.2 Effect of curing pressure on the microstructure

Pressurized curing promotes the rapid expulsion of free pore water from the interior of CPB specimens and induces pore closure, which directly tailors the microstructure of the cementitious matrix. As presented in Figure 11, under a constant curing temperature of 45 °C, the number of internal pores in CPB specimens decreases significantly with increasing curing pressure, accompanied by a denser overall microstructure, which corresponds to the continuous improvement in the macroscopic mechanical strength of CPB. A remarkable difference in microstructure is observed between the unpressurized specimen (Figure 11(a)) and the specimens cured under pressurized conditions.

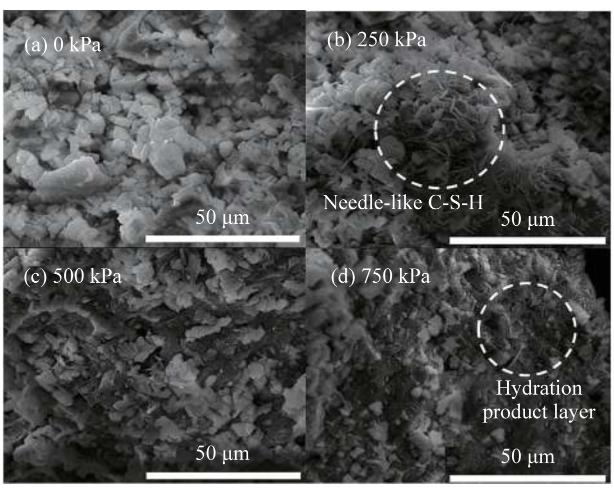

Figure 11 SEM micrographs of CPB specimens under different curing pressures (curing age:3 days)

Figure 11(b) shows that at a low curing pressure of 250 kPa, the hydration products mainly exhibit an acicular rod-like morphology, which are discretely distributed between the tailings particles. In contrast, with the elevation of curing pressure (Figures 11(c) and 11(d)), a continuous and dense hydration product layer is formed between adjacent solid particles. No discrete acicular, rod-like, or flocculent hydration products can be identified at the corresponding observation scale.

4.3.3 Effect of curing temperature on the microstructure

According to the monitoring results of the strength development process of CPB in the previous section, with the increase of curing temperature, the internal volumetric water content and electrical conductivity of the backfill first increase and then decrease, indicating that the degree of hydration reaction inside the backfill first increases and then decreases.

At a curing pressure of 250 kPa, the scanning electron microscope results of the specimens under different curing temperatures are shown in Figures 4–16. The SEM image results show that when the curing temperature rises from 20 through 35 to 45 °C, the internal hydration reaction of the backfill becomes more sufficient, and the hydration product C-S-H increases significantly. At curing temperatures of 20 and 35 C, as shown in Figures 12(a) and 12(b), a small amount of acicular and rod-like hydration reaction products exist, which is consistent with the standard curing specimens at the same magnification. In contrast, when the curing temperature reaches 45 °C, a large number of acicular and rod-like C-S-H products appear, as shown in Figure 12(c), which indicates that the internal hydration reaction degree of the backfill is higher; the hydration reaction products are more abundant, and the strength of the cemented paste backfill is higher at this time. On the contrary, when the curing temperature is 55 °C, the C-S-H gel is significantly reduced. It indicates that under the condition of 55 °C, the internal hydration reaction of the cemented paste backfill is inhibited, the yield of the hydration product C-S-H gel is low, and the mechanical properties of the backfill are reduced compared with the specimens cured at 45 °C.

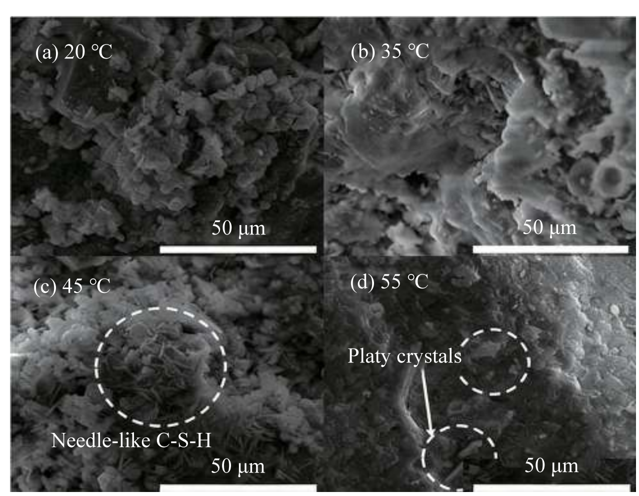

Figure 12 SEM micrographs of CPB specimens under different curing temperature (curing age: 3 days)

4.3.4 Effect of pore water pressure on the microstructure

Pore water pressure can cause damage to CPB. To make the results more obvious, specimens with a curing pressure of 750 kPa were used for the test. As shown in Figure 13, the application of pore water pressure leads to a loose microscopic morphology of the backfill specimens, with a large number of interconnected pores appearing, which causes strength reduction of the cemented paste backfill specimens and is not conducive to the mechanical properties of the backfill.

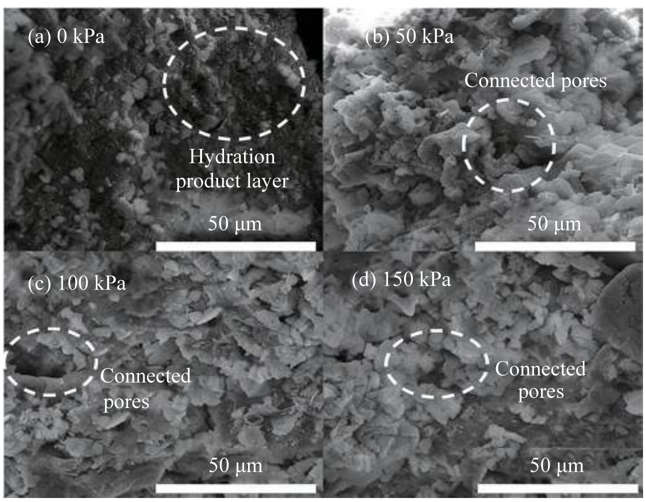

Figure 13 SEM micrographs of CPB specimens under different pore water pressure (curing age:3 days)

5 Conclusion

This paper systematically reviews the research on the effect of *in-situ* stope environment on mechanical properties of CPB, analyzes research gaps from the perspectives of curing pressure, temperature, pore water pressure and curing apparatus, and clarifies CPB mechanical evolution and underlying mechanisms under multi-field coupling via tests on a self-developed *in-situ* environment physical twin apparatus. Main conclusions are as follows:

(1) Mechanical properties of CPB dominate stope backfill stability in metal mines, and clarifying its *in-situ* mechanical evolution is critical for backfill mix optimization. Most existing studies focus on single factors, inconsistent with the actual mine thermal-hydraulic-mechanical (THM) coupling environment. The physical field-twin test apparatus for backfill *in-situ* environment developed in this work enables synchronous simulation of *in-situ* curing pressure, temperature, and pore water pressure, providing a reliable experimental platform for relevant research.

(2) The UCS of CPB first increases and then decreases with rising temperature, peaking at the optimal hydration temperature of 45 °C; further heating reduces strength via thermal expansion-induced pore damage. The CPB UCS rises with curing pressure, which closes pores, promotes drainage and hydration, while the strength gain diminishes sharply after full compaction. The Pore water pressure directly reduces CPB strength, opposite to curing pressure.

(3) The optimal curing temperature (45 °C) maximizes hydration, promotes C-S-H gel formation, and strengthens inter-particle cementation; pressurized curing densifies pore structure and hydration product distribution; pore water pressure induces pore-crack initiation, breaks structural continuity, and deteriorates mechanical properties of CPB.

Credit authorship contribution statement

Caixing Shi: data curation, writing-original draft.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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