Cemented Backfill Twin Curing Apparatus Coupled with THMC Effect and *In Situ* Backfill Strength Estimation

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Abstract
Cemented backfill is a mixture comprising dewatered tailings, a cementitious binder, and treated mine water. It is used to fill excavated cavities created during underground mining operations. Once placed in excavated cavities, the backfill material undergoes thermal (T), hydraulic (H), and mechanical (M; including self-weight and stress from surrounding rock mass) processes, along with THM coupling effects. Consequently, the mechanical properties of *in situ* cemented paste backfill (CPB) can vary significantly from laboratory results. Relying solely on laboratory data for backfill design may result in underestimated or overestimated strength, potentially increasing backfill costs and compromising safety and stability in mining stopes. This study introduces a Cemented Backfill Twin Curing Apparatus (TCA) integrated with the THM effect to assess how the *in situ* Thermal-Hydraulic-Mechanical environment affects the mechanical properties of backfill material. Subsequently, the TCA was employed to create paired CPB samples, which were subjected to *in situ* curing, followed by a series of macro experiments aimed at uncovering the interrelationships between cemented backfill strength and multifactor coupling effects. These findings have the potential to enhance the design of cost-effective, stable, durable, and environmentally friendly backfill structures.

Key words: cement paste backfill, *in situ* condition, THM effect, twin curing apparatus, strength estimation

Introduction
In recent decades, the mining industry has produced substantial annual quantities of tailings during the mineral processing phase of ore extraction (Jones and Boger 2012; Öhlander et al., 2012; Guo et al., 2022). Traditionally, these waste tailings have been deposited in surface storage facilities commonly known as tailings ponds. However, this conventional approach to tailings storage can pose significant environmental risks, contribute to geotechnical instability at mine sites, and present economic challenges (Zhao et al., 2019; Xu et al., 2018). In response, CPB has gained popularity in the mining industry. CPB involves filling underground voids left by mining with waste tailings. This method not only offers an alternative for tailings disposal but also reduces the volume of tailings requiring surface disposal and enhances underground mine stability (Zhao et al., 2020; Sivakugan et al. 2015; Benzaazoua et al. 2004). Compared to other backfill techniques, such as rock fills and hydraulic fills, CPB boasts superior mechanical performance, lower operating costs, and the added advantage of underground tailings disposal (Benzaazoua et al., 2004; Ouattara et al., 2017).

Extensive research has investigated the factors influencing CPB's mechanical performance, including the tailings' particle size distribution, chemical composition, binder type and content, water content and chemical composition, curing temperature, and drainage conditions. However, it has been observed that the conventional method of sample preparation (using moulds) tends to underestimate the actual *in situ* mechanical performance of CPB when compared to laboratory tests (le Roux et al., 2013; Thompson et al., 2012). This discrepancy arises from differences in the sample curing environments between the laboratory and *in situ* sites, as well as from THM effects and their interactions (THM coupling effects). Existing studies have researched the individual THM impacts on CPB performance. The mechanical load effect, primarily due to the self-weight of the backfill and the stress from the surrounding rock, is a crucial factor. Benzaazoua et al. (2006) and Yilmaz et al. (2014) introduced the Curing under Applied Pressure System (CUAPS). In this system, CPB samples are subjected to a maximum of 400 kPa axial stress during curing. The uniaxial compressive strength (UCS) of these samples was found to be significantly higher compared to those without such pressure, indicating improved mechanical properties (Belem and Benzaazoua, 2008; Zhou and Beaudoin, 2003; Zhao et al., 2021). Temperature also plays a vital role. For instance, the heat generated by cement hydration in backfilled stopes can cause internal temperatures to soar up to 50°C, much higher than the standard 20°C curing temperature in labs (Nasir and Fall, 2009). Fall and Samb (2009) noted that the impact of curing temperature on CPB strength varies: it can enhance mechanical properties at lower temperatures but reduce them at excessively high temperatures due to thermal expansion and stress-induced microcracks. Similarly, the effects of different hydraulic water pressures on CPB mechanical properties were explored by Zhou et al. (2019), who used a centrifuge to simulate underground seepage at varying speeds. Their findings indicated that increasing hydraulic pressure generally decreases the compressive strength of CPB, affects its elastic modulus, and reduces peak strain.

This study introduces the Twin Curing Apparatus (TCA), considering all three (thermal, hydraulic, and mechanical) environmental variables designed to simulate *in situ* conditions by controlling temperature, hydraulic pressure, and axial stress. Using tailings from a Gold mine in Shandong Province, China, this research aims to investigate the early strength characteristics of cemented paste backfill under combined pressure and temperature conditions using the TCA.

Twin curing apparatus coupled with THM effect

The TCA has been innovatively designed to replicate the *in situ* TCM conditions found within an actual backfilled mine stope during the curing process. Building upon the Curing under Pressure Apparatus (CPA) developed by Zhao et al. (2021), which was initially designed to simulate the *in situ* pressure conditions for CPB samples, the TCA further incorporates temperature and hydraulic control mechanisms.

The TCA allows for the adjustment of temperature, hydraulic back pressure, and mechanical load (Figure 1). At the top of the TCA structure, a hydraulic pump was used to provide the axial load. The load could then be transferred to the top of the CPB sample during curing through a PVC piston. Outside the mould of the sample, a constant temperature chamber with a temperature controller was used to control the temperature. On the base plate, a steel tubing system was used to connect the bottom of the mould (sample) and an Advanced High Pressure/Volume Controller (Global Digital Systems Ltd, Hampshire, UK), which allows the adjustment for *in situ* pore pressure.

This functionality enables the simulation of the stope's *in situ* environment and facilitates the preparation of Twin CPB specimens under these controlled conditions. Subsequent experiments on these specimens, such as Uniaxial and Triaxial Compression Tests and Scanning Electron Microscopy analysis, can be conducted to assess the impact of thermal, hydraulic, and mechanical factors, as well as the combined THM coupling effects on the properties of CPB. This approach provides a more comprehensive understanding of the behavior of CPB under conditions that closely resemble those in actual mining environments.

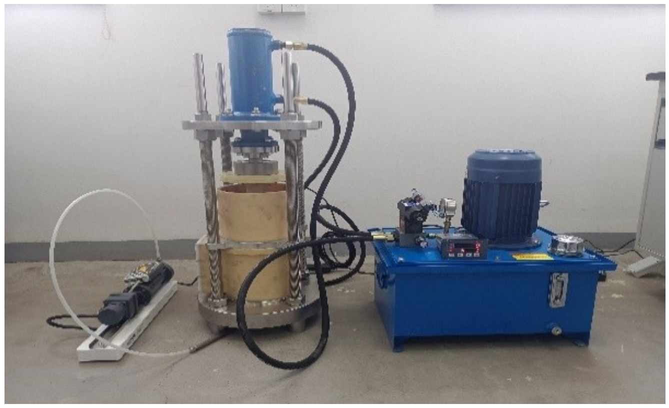

Figure 1. Twin Curing Apparatus (TCA).

Materials and experimental setups
Materials
Mine Tailings
The tailings material utilized in this study was procured from the vertical sand silo of a Gold mine located in Shandong Province, China (Figure 2). The initially slurry-formed tailings were air-dried and subsequently mixed to achieve homogeneity, preparing them for further sample analysis. Figure 3 details the particle size distribution of these tailings, revealing a composition of 23.5% fine grains < 74 µm and 17.8% ultra-fine grains < 37 µm. The characterization of the tailings sample demonstrated a specific gravity (Gs) of 2.77, a bulk density of 1.34 g/cm³, and a porosity of 51.75%. Additionally, a comprehensive chemical composition analysis was conducted (Table 1), the predominant component of the tailings is silicon dioxide (SiO_2), constituting 76.22% of the material. Other significant constituents include potassium oxide (K_2O) at 3.37%, iron oxide (FeO) at 2.1%, and sulfur trioxide (SO_3) at 1.5%.

Figure 2. Air-dried tailings from a Gold mine in Shandong Province, China.

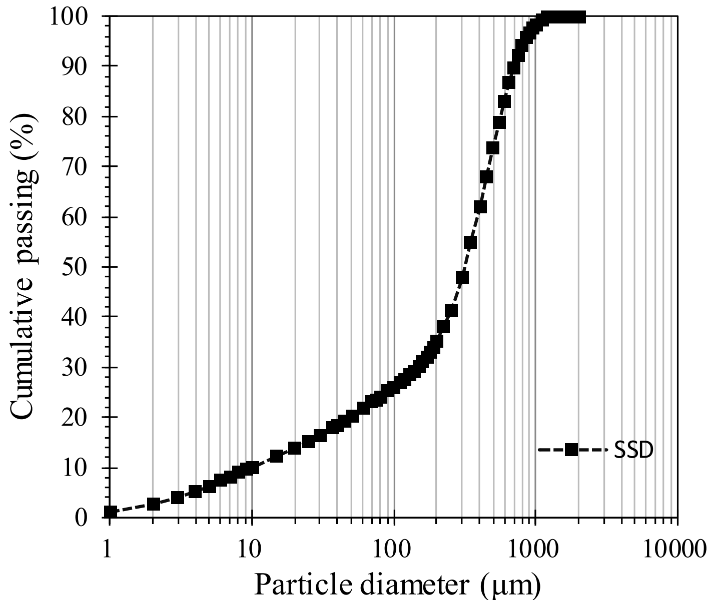

Figure 3. Particle size distribution of tailings.

Table 1. Chemical composition of tailings.

Component	SiO_2	Al_2O_3	MgO	FeO	CaO	TiO_2	P_2O_5	K_2O	Na_2O	SO_3
Content (%)	76.22	0.93	0.50	2.10	1.20	0.10	0.05	3.37	0.50	1.50

Binder and Water
In this study, the cement employed was P.O 42.5 ordinary Portland cement (OPC), characterized by a density of 3.10 g/cm³ and a specific surface area of 343 m²/kg. The chemical composition of this OPC primarily consists of calcium oxide (CaO), which accounts for 61.16% of its makeup (Table 2). Additionally, silicon dioxide (SiO_2) constitutes 21.46%, and aluminium oxide (Al_2O_3) makes up 4.38% of the cement. The mixing water used in the preparation was processed water obtained from the same Gold mine in Shandong Province, China, ensuring consistency in the materials' source and quality for the study.

Table 2. Chemical composition of ordinary Portland cement.

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2Oeq	MnO	TiO_2
Content (%)	61.18	21.46	4.38	3.41	2.43	2.46	0.59	0.12	0.09

Experiment setup
Sample Preparation
For this study, based on the requirements of the mine, a solid content of 72% by weight and a cement-to-sand ratio of 1:10 (equivalent to 9.09% binder content) were selected. Consequently, only one binder content (9.09% OPC) and one solid content (72%) were employed throughout the research. The tailings and OPC were initially mixed in dry states using a bakery mixer. Following this, the requisite amount of processed mine water was added to attain a slurry with 72% solid content. This mixture was then blended for approximately 5 mins to ensure homogeneity. Once adequately mixed, the slurry was ready to be poured into the Twin Curing Apparatus (TCA), set to the designated temperature, hydraulic pressure, and mechanical load.

For the purpose of this experiment, four distinct mechanical load stress levels were chosen: 0, 250, 500, and 750 kPa. Additionally, two temperature levels were selected: 35 and 55℃. A control condition with 0 kPa axial load and a curing temperature of 20℃ was also included to serve as a reference, representing standard laboratory curing conditions. Altogether, this resulted in nine distinct curing designs being prepared and evaluated in the study with a curing period of 3 days.

Uniaxial Compression Tests

In compliance with the ASTM C39 standard, uniaxial compression tests were conducted on CPB samples. These tests were performed using a Humboldt HM-5030 closed-loop servo-controlled testing machine manufactured in the USA, which has a maximum loading capacity of 50 kN. The machine's loading rate for the uniaxial compression tests was precisely set to 0.1 mm/min. This standardized approach ensures that the test results are reliable, reproducible, and can be accurately compared with other studies following the same standards.

Result and discussion

Uniaxial compressive strength (UCS) is a critical metric for assessing the mechanical performance of CPB. Table 3 provides a comprehensive overview of the UCS values for samples that underwent a 3 day curing period. These samples were prepared using the nine distinct curing designs, which varied in temperature and axial stress. This table offers valuable insights into how different curing conditions influence the UCS of CPB, thereby contributing to a deeper understanding of the material's mechanical properties under various environmental factors.

Table 3. Uniaxial compression test results for CPB under the different curing temperature and pressure.

Axial load (Curing Pressure) kPa	Curing temperature ℃	UCS/MPa			
		Sample1	Sample 2	Sample 3	Average
0	20	0.68	0.74	0.61	0.68
0	35	0.89	0.82	0.81	0.84
0	55	0.68	0.67	0.70	0.68
250	35	1.13	1.14	1.16	1.14
250	55	1.78	1.85	1.77	1.80
500	35	1.57	1.60	1.68	1.61
500	55	2.51	2.46	2.54	2.50
750	35	2.31	2.47	2.39	2.39
750	55	2.55	2.43	2.64	2.54

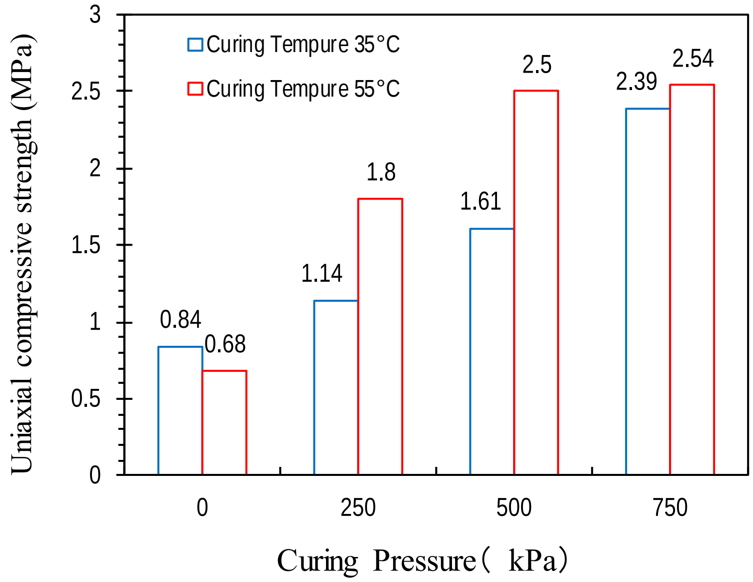

Figure 4. Influence of curing pressure and curing temperature on early strength of cemented backfill.

Figure 4 demonstrates the influence of curing pressure and temperature on the early strength of tailings cemented backfill. Test results unequivocally indicate that both curing pressure and temperature substantially affect the early strength of CPB; increasing curing pressure positively enhances the CPB's early strength. Conversely, the impact of curing temperature on the early strength of CPB is multifaceted and complex, suggesting a nuanced interplay between thermal conditions and the material's early strength development.

Figure 5 illustrates that under a constant curing temperature, the UCS of the CPB increases with rising curing pressure, and the rate of this increase is dramatically influenced by the curing temperature. Specifically, at a curing temperature of 35°C, starting from a curing pressure of 0, each increment of 250 kPa results in corresponding UCS increases of 35.7, 41.2, and 48.4%, respectively. This trend indicates a progressively positive relationship between curing pressure and the strength of the CPB sample.

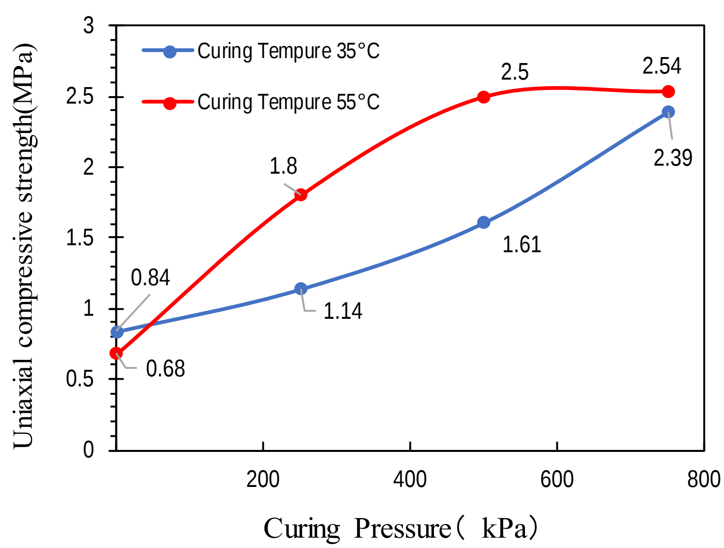

Figure 5. Effect of curing pressure on UCS of CPB.

However, at a higher curing temperature of 55°C, the increases in UCS for each 250 kPa increment are 164.7, 38.9, and 1.6%, respectively. In this scenario, a low curing pressure markedly enhances the UCS of the CPB sample. However, as the curing pressure increases, further increases yield only marginal improvements in UCS. This suggests that at 55°C, once a certain curing pressure threshold is reached, additional pressure contributes minimally to further strengthening the CPB sample.

This observed phenomenon occurs when the CPB sample, with a solid content of 72% and a binder content of 9.09%, reaches its maximum potential UCS. Under conditions of 55℃ curing temperature and 500 kPa curing pressure, the internal pores of the CPB are compacted, and the hydration reaction is expedited. Consequently, once the CPB specimen attains this level of strength, further increases in curing temperature or pressure do not significantly enhance the UCS. Conversely, a low UCS in the CPB suggests either an incomplete hydration reaction or a high porosity. Under these circumstances, alterations in curing temperature or pressure substantially affect the UCS, highlighting the critical role of these factors in the development of the CPB's mechanical properties.

During the curing process under applied pressure, the strength of the CPB sample is observed to increase with the rise in curing temperature. However, in the absence of curing pressure, the UCS behaves differently: it initially increases as the temperature rises from 20℃ to 35℃ but then decreases at 55℃. This pattern can be attributed to the state of the slurry during the early consolidation phase, which is characterized by a solid-liquid transition. When subjected to curing under pressure, the slurry enters a compaction stage early in the curing process, leading to a reduction in pores or cracks and the expulsion of free water. Elevating the curing temperature under these conditions hastens the evaporation of this free water, thereby further enhancing the CPB sample's strength. Conversely, when no curing pressure is applied, a high temperature causes excessive evaporation of free water. This excessive evaporation can lead to the expansion of pores or cracks within the CPB due to the water's vaporization, ultimately resulting in a decrease in the strength of the CPB sample.

In the absence of curing pressure, the UCS of the CPB specimen initially increases and then decreases with rising curing temperature (Figure 6). This observation aligns with the findings of previous studies by Fall and Samb (2009), Xu et al. (2018), and Wang (2017). The initial increase in strength can be attributed to the enhanced cement hydration reaction within the slurry, prompted by the increase in curing temperature. This accelerated hydration reaction facilitates the consolidation of the slurry, thereby improving the early strength of the CPB. However, at excessively high temperatures, the strength of the specimen diminishes due to the expansion of micro-cracks within the CPB sample caused by thermal effects. This dual impact of curing temperature highlights the critical balance between promoting hydration reactions and avoiding thermal-induced damage within the CPB structure.

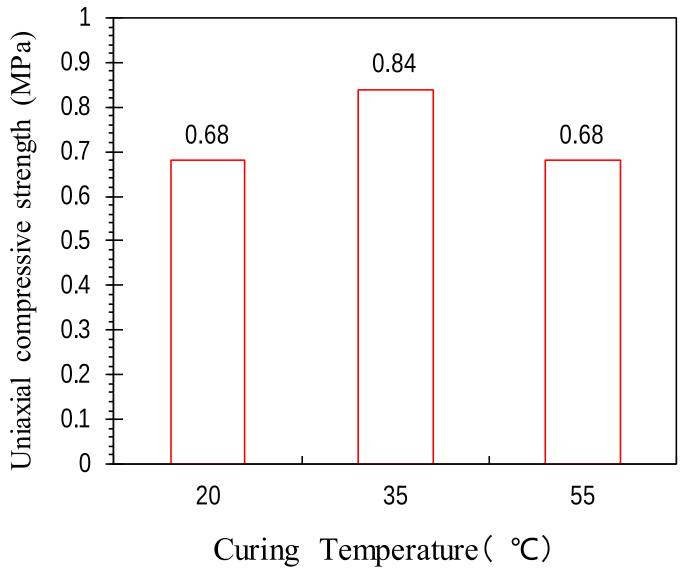

Figure 6. Effect of curing temperature on the UCS of CPB.

The strength of a CPB sample is fundamentally influenced by its internal structure, including pores, cracks, and other formations. During the consolidation of CPB slurry, the hydration reaction is produced, which interconnects the aggregates within the slurry, thus reducing internal porosity and consequently enhancing the uniaxial compressive strength of the CPB. However, excessive internal porosity can lead to an abundance of free water in the pores, diluting the slurry and impeding the cement hydration reaction. In contrast, if the internal porosity is too low, the elimination of free water may inhibit the hydration reaction due to a lack of water, adversely affecting the development of uniaxial compressive strength.

In curing tests, the role of curing pressure is to compact the CPB sample, thereby reducing its internal pores. Conversely, curing temperature primarily influences the strength of the CPB sample by affecting the cement hydration reaction during slurry consolidation and altering the size of pores or cracks through thermal expansion. Notably, the compaction of pores due to curing pressure mainly occurs in the early stages of slurry consolidation. In contrast, thermal expansion impacts the size of pores or cracks throughout the entire consolidation process. As a result, in the early stages of slurry consolidation, the strength of the cemented paste backfill is predominantly affected by the curing pressure.

Conclusion

In this study, a TCA was developed to simulate the *in situ* thermal THM conditions experienced in a real backfilled mine stope during curing. Four mechanical load stress levels (curing pressures) of 0, 250, 500, and 750 kPa, along with two temperature levels of 35 and 55°C, were selected for testing. Additionally, a condition of 0 kPa axial load and 20°C curing temperature served as the reference for standard laboratory curing conditions, leading to a total of nine distinct curing designs in the study. UCS tests were conducted on these nine mix designs after a 3 day curing period, yielding the following conclusions:

1. CPB samples cured under increasing applied pressure and temperature exhibited significantly higher uniaxial compressive strength compared to those cured under standard laboratory conditions.
2. Curing pressure positively affects the early development of uniaxial compressive strength of the CPB, with strength increasing alongside curing pressure.

3. The impact of curing temperature on the early uniaxial compressive strength of CPB samples is conditional; only an optimal curing temperature enhances the early strength of the CPB sample, whereas temperatures that are either too high or too low hinder its development.
4. A notable discrepancy exists between the strength of *in situ* CPB samples and those prepared in the laboratory. Standard laboratory-cured CPB samples do not accurately reflect the strength within an actual backfill stope. The TCA can be utilized in mines to prepare twin CPB samples for a more accurate estimation of in situ CPB strength.
5. In this study, only curing pressure and curing temperature were considered and adjusted using the TCA, and the primary purpose of this part of the research is to verify the reliability of the apparatus. With the TCA, after the *in situ* measurement of in-stope environmental (THM) factors, a twin cemented paste backfill specimen could be prepared through TCA under the exact same curing condition, the *in situ* mechanical properties of CPB could be precisely detected without the coring of *in situ* CPB stope. In addition, further orthogonal tests will be done under various THM conditions to establish a model for *in situ* backfill strength estimation, along with additional microanalysis for more comprehensive insights.

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