

Article

The Mechanical Properties and Microstructural Characterization of Copper Tailing Backfill Cemented with a Slag-Based Material

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Abstract

To address the challenges associated with Ordinary Portland Cement (OPC) in mine backfilling, including high costs, the large carbon footprint, and performance limitations, a novel cementitious powder (CP) based on alkali-activated slag is developed in this work. The mechanical performance and microstructural strengthening mechanism of this CP as a substitute for OPC in cemented copper tailing backfill (CTB) were systematically evaluated. The effects of key parameters, including the solid content (SC), tailing-to-cement ratio (TCR), and curing age (CA), were investigated using uniaxial compressive strength (UCS) tests and scanning electron microscopy (SEM) analysis. The results demonstrate that the novel binder exhibits superior performance. At a solid content of 73%, the CTB prepared with CP at a TCR of 10 or 12 achieved a compressive strength comparable to or exceeding that of the OPC-based counterpart with a TCR of 8. This represents a 33% reduction in binder dosage without sacrificing performance. The UCS of the CTB increased significantly with a decreasing TCR and an increasing CA, with the most rapid strength development observed during the early curing stages (≤ 7 days). The stress–strain behavior transitioned from plastic yielding to strain-softening with prolonged curing, and the macroscopic failure was predominantly governed by tensile cracking. Microstructural analysis revealed that the strength development of the CTB originates from the continuous formation of hydration products, such as calcium-silicate-hydrate (C-S-H) gel and ettringite. These products progressively fill pores and encapsulate tailing particles, creating a dense and interlocking skeletal structure. A lower TCR and a longer CA promote the formation of a more integrated and compact micro-network, thereby enhancing the macroscopic mechanical strength. This study confirms the viability of the slag-based binder as a sustainable alternative to OPC in mining backfill applications, providing a critical theoretical basis and technical support for the low-cost, eco-friendly utilization of mining solid waste.

Keywords: cement tailing backfill; alkali-activated slag; uniaxial compressive tests; failure mode; microstructure; tailing-to-cement ratio



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1. Introduction

The exploitation of mineral resources has significantly contributed to economic growth worldwide, yet it has also produced vast quantities of mine tailings and goafs, posing serious environmental and geotechnical risks [1–4]. In China, approximately

1.28 billion m³ of underground goafs and more than 14 billion tons of accumulated tailings have been reported, with the accumulation increasing at a rate of about 600 million tons annually [5,6]. More critically, these by-products cause land subsidence and threaten underground stability [3,6,7], while the surface deposition of tailings occupies valuable land and contaminates air, groundwater, and soil [8–10]. Therefore, large-scale management and reuse of tailings have become an urgent requirement for sustainable mining.

Cemented tailing backfilling (CTB) is an effective technique for mitigating these environmental hazards and maintaining ground stability. It involves mixing tailings, solid waste, water, and cementing binders to form a pumpable slurry that solidifies in the mined-out voids [2,6,9–11]. CTB provides mechanical support for stopes, controls ground pressure [12], and reduces surface subsidence [13] while improving ore recovery efficiency [14,15]. Consequently, it has become a standard practice in underground mining worldwide. The uniaxial compressive strength (UCS) is the most critical indicator for evaluating the safety and mechanical stability of CTB [16,17]. Its development is affected by factors such as curing conditions, binder type and dosage, solid content (SC), and the tailing-to-cement ratio (TCR) [18–22]. Among these, TCR is significant, as it governs both strength evolution and backfilling cost [23].

Ordinary Portland cement (OPC) remains the most widely used binder in CTB due to its reliable performance and availability. However, its high unit cost and large carbon footprint [24,25] contradict the current objectives of low-carbon mining and green development. In addition, OPC exhibits poor adaptability to fine-grained tailings, which are increasingly common in modern beneficiation operations. The high proportion of fines leads to low slurry concentration, excessive bleeding, and inadequate consolidation [26,27]. These drawbacks limit the filling efficiency and the long-term stability of the backfill structure. Hence, the search for alternative binders that can achieve comparable or superior strength with lower cost and reduced environmental impact has become a significant research focus.

In recent times, a growing body of research has explored the partial or complete replacement of OPC with industrial by-products and pozzolanic materials such as blast furnace slag, fly ash, and silica fume [28–34]. Among these, slag-based and fly ash-based systems have demonstrated promising mechanical and environmental performance [11,30,31]. Zhang et al. [35] reported that the inclusion of fly ash improved the tensile strength of gold tailing-based geopolymers up to an optimum dosage. Sari et al. [36] showed that CTB prepared with blast furnace slag binders exhibited markedly higher UCS than those containing fly ash under both low and high pH conditions. Zhang et al. [37] found that a slag-based cementitious material achieved equivalent 28-day strength using only half of the OPC dosage, while Jiang et al. [38] demonstrated that alkali-activated slag binders with sodium silicate and sodium hydroxide activators provided excellent early-age strength. Similar results were obtained by Xue et al. [39] and Eker and Bascetin [11], who confirmed the feasibility of using silica fume or alkali-activated fly ash as sustainable alternatives to OPC. While previous studies have demonstrated the potential of alkali-activated slag binders for mine backfill [6,13,22], several gaps remain. First, most studies focus on generic tailings, lacking a specific investigation into the performance and interaction of AAS binders with challenging fine-grained copper tailings. Second, the practical application of AAS is often hindered by the use of two-part, liquid-activated systems; a stable, pre-formulated, one-part powder binder designed for engineering convenience is still underexplored. Most critically, a systematic demonstration of a quantifiable performance advantage, specifically, the ability to achieve equivalent or superior strength at a significantly lower binder dosage, has not been established. This study aims to bridge these gaps

by developing and validating such a high-performance, one-part slag-based powder for cemented copper tailing backfill.

In this context, a novel slag-based cementitious powder (CP) is developed and activated by alkaline agents. This new powder is designed as a sustainable substitute for OPC in copper tailing backfill. The formulation of CP was optimized to balance mechanical strength and cost efficiency, and its potential to replace OPC was systematically evaluated. The effects of solid content (SC), tailing-to-cement ratio (TCR), and curing age (CA) on the UCS, stress–strain behavior, and failure characteristics of CTB were investigated through laboratory testing. Furthermore, scanning electron microscopy (SEM) was employed to elucidate the microstructural evolution and hydration mechanisms underlying the observed strength development. The main structure of this paper is as follows: Section 2 systematically presents the composition of the cementitious agent and tailings, the sample preparation process, and a range of instruments and techniques utilized for testing. In Section 3, the feasibility of replacing OPC with the developed cementitious materials is discussed in depth, and the mechanical properties (including strength characteristics, deformation characteristics, and failure modes) associated with the strength enhancement mechanism of CTB prepared with the developed cementitious materials are discussed. A conclusion section is offered at the end of this paper.

2. Materials and Experimental Method

2.1. Material Characterization

The full tailings (FTs) utilized in this investigation were sourced directly from the effluent outlet of the paste filling station at the Wushan copper mine. To facilitate an efficient drying process, the as-received tailings slurry was initially decanted by storing it in multiple plastic containers for seven days, after which the supernatant water was carefully removed. The remaining sediment was subjected to complete dehydration in a drying oven at a constant temperature until a constant mass was achieved, signifying the removal of all free moisture. This oven-dried tailings material and the developed cementitious binder were then used to fabricate the backfill specimens for subsequent characterization of their physical properties and chemical composition.

The fundamental physical properties of the tailings were determined as follows: a specific gravity of 2.6, an apparent porosity of 56.27%, and a void ratio of 2.29. The grain size distribution (GSD) was characterized using a Winner 2000 laser particle size analyzer (Jinan Winner Instrument Particle Stock Co., Ltd. Jinnan, China), with the results graphically presented in Figure 1. Key physical parameters of the FT are concisely summarized in Table 1. Based on the gradation theory [40] and the experimentally obtained GSD curve, the coefficients of uniformity (C_u) and curvature (C_c) for the FT were calculated to be 12.53 and 1.31, respectively. These values indicate that the tailings are well-graded. For this study, a novel cementitious material (designated as CP, for cementitious powder) was developed as an alternative to OPC, formulated using ground granulated blast-furnace slag as the primary precursor and alkaline chemicals (NaOH) as activators. The CP is a one-part, pre-blended binder. The activator consists primarily of sodium hydroxide combined with sodium silicate powder. The components are homogenized in a specific ratio (7:3 slag-to-activator by mass) to ensure consistent reactivity when mixed with water. The sodium silicate modulus is 1.1. This one-part formulation distinguishes it from standard two-part alkali-activated systems, simplifying on-site logistics and handling.

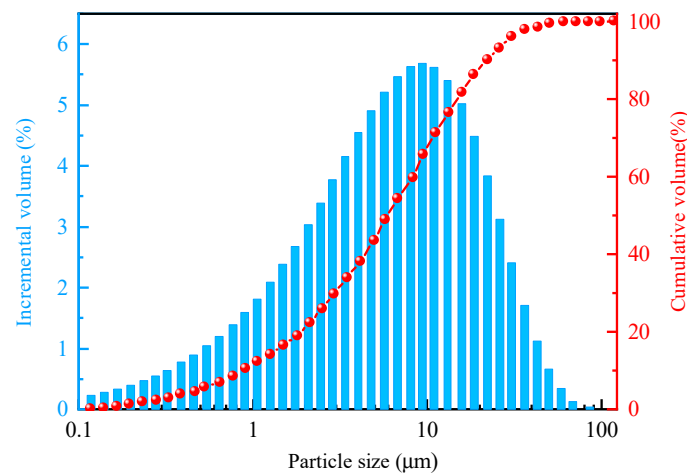


Figure 1. Grain size distribution of FTs in Wushan copper mine.

Table 1. Key indicators of physical properties of FT in Wushan copper mine *.

Key Indicators	G_s	d_{10} (μm)	d_{30} (μm)	d_{50} (μm)	d_{60} (μm)	C_u	C_c
FT	2.6	1.1	4.6	10.2	14.3	12.53	1.31

* G_s : specific gravity; C_u : coefficient of uniformity, defined as d_{60}/d_{10} ; C_c : coefficient of curvature, defined as $d_{30}^2/d_{60} \times d_{10}$.

The chemical composition of FTs and CP was analyzed by using a Rigaku intelligent multi-function X-ray diffractometer. The results are presented in Figure 2 and Table 2. The main chemical component of FTs is SiO_2 (68.7%), which is chemically stable and can be used as a filling aggregate in deep mining, while the main chemical component of CP is CaSO_4 (60.5%).

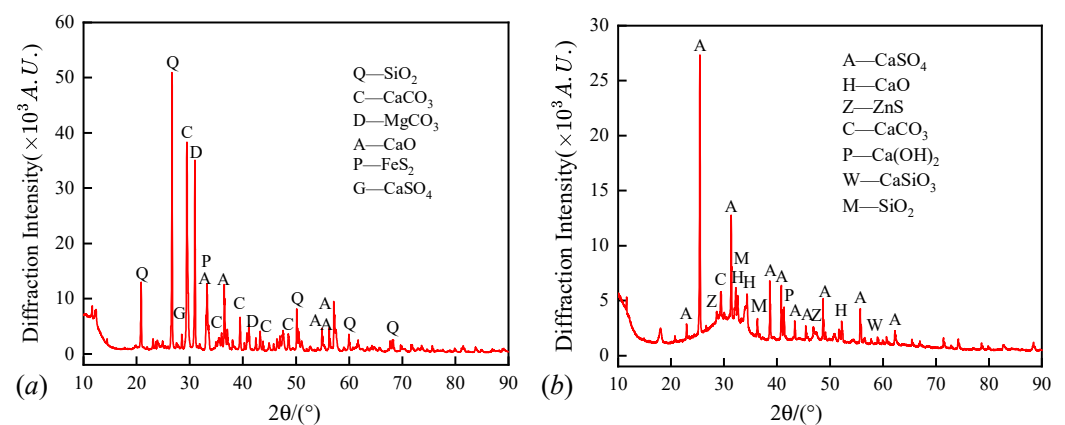


Figure 2. Comparison of XRD patterns of (a) FTs and (b) CP.

Table 2. Chemical composition (wt.% ≥ 2) of FTs and CP.

Composition	CaSO_4	CaO	CaSiO_3	MgCO_3	SiO_2	ZnS	FeS_2	Ca(OH)_2	Al_2O_3
FT (wt.%)	5.3	7.8	-	3.8	64.9	-	7.8	-	7.1
CP (wt.%)	60.5	13.1	7.1	7.0	4.4	2.7	-	2.6	-

2.2. Sample Preparation and Loading Procedures

2.2.1. Sample Manufacturing/Curing

We prepared cemented tailing backfill (CTB) specimens in accordance with the Chinese standard JGJ/T 70–2009 [41]. Initially, full tailings (FTs), the novel cementitious powder

(CP), and tap water were combined in predetermined proportions and mechanically homogenized using an electric mixer (Shanghai Meiyongpu Instrument and Meter Manufacturing Co., Ltd., Shanghai, China) for 3 min, yielding a uniform paste slurry. This prepared mortar was immediately poured into 70.7 mm standard cubic triple-gang molds. The cast specimens were allowed to cure for 24 h under ambient laboratory conditions before being demolded. As outlined in Table 3, the test program was designed to investigate a range of parameters, including solid content (SC), tailing-to-cement ratio (TCR), and curing age (CA), which were chosen to simulate the operational status at the Wushan copper mine.

Table 3. Preparation program of the CTB.

Mechanical Testing	SC (wt. %)	TCR	CA (Day)
Uniaxial compressive test	71, 72, 73, 74	6, 8, 10, 12, 14, 16	1, 3, 7, 14, 28
Micro scanning test	71, 72, 73, 74	6, 8, 12	3, 7, 14, 28

Following demolding, all specimens were sealed to prevent water loss and placed in a standard curing environment. They were cured at a constant temperature of 25 °C and a relative humidity of $\geq 85\%$ for 1, 3, 7, 14, and 28 days. At the end of each designated curing interval, the samples underwent a series of characterization tests to evaluate their properties, including mechanical assessments and microstructural scanning examinations. A detailed schematic diagram illustrating the overall experimental procedure is provided in Figure 3.

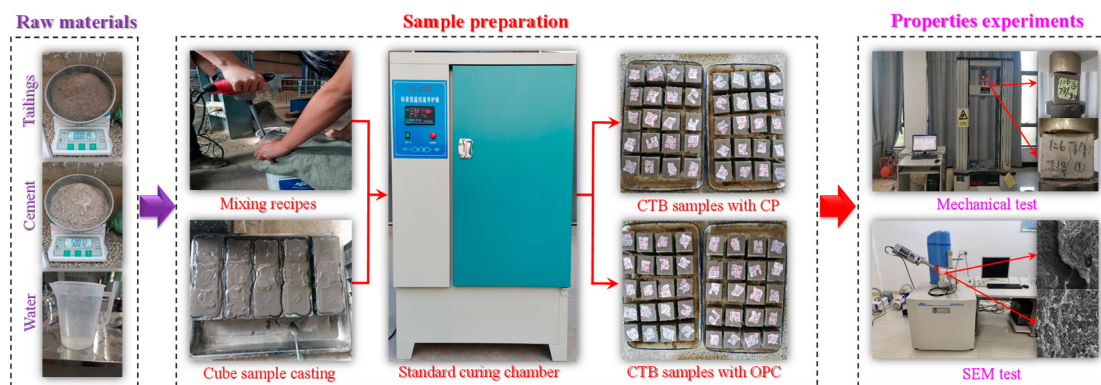


Figure 3. Main technical route of CTB preparations and tests.

2.2.2. Mechanical Test

The mechanical strength of the CTB is a critical parameter for ensuring the safety and long-term stability of underground mining operations. In this study, the UCS of the CTB specimens was determined at designated curing ages of 1, 3, 7, 14, and 28 days. The tests were performed using a ZTRE-210 universal testing machine (Changchun Tuozhan Experimental Instrument Co., Ltd., Jilin, Changchun, China) with a maximum loading capacity of 100 kN. A strain-controlled loading mode was employed, with a constant axial displacement rate of 0.1 mm/min applied until failure. To ensure reliability and minimize the effects of data dispersion, each UCS measurement was conducted in triplicate for every test condition. The final reported UCS for each condition represents the arithmetic mean of the three replicate tests. A visual depiction of the experimental setup for the loading test is provided in Figure 3.

2.2.3. Scanning Electron Microscopy (SEM) Test

To elucidate the micro-level mechanisms governing strength development, the influence of SC, TCR, and CA was investigated through Scanning Electron Microscopy (SEM).

The analyses were performed on representative CTB specimens using a JEM-8510 SEM operating (JEOL Ltd., Tokyo, Japan) at an accelerating voltage of 35 kV. This technique was employed to examine key microstructural features, including the morphology of hydration products, microcrack distribution, pore structure characteristics, and overall internal fabric of the CTB matrix post-failure. For this purpose, small fragments, with dimensions not exceeding $5\text{ mm} \times 5\text{ mm} \times 5\text{ mm}$, were carefully extracted from the fractured zones of the specimens after mechanical testing. Before SEM imaging, these fragments were oven-dried to eliminate residual moisture that could interfere with the analysis, and sputter-coated with a thin layer of carbon to ensure electrical conductivity. Representative micrographs obtained from the SEM analysis and the testing instrumentation are presented in Figure 3.

3. Results and Discussion

3.1. Technical Parameter Optimization

OPC is currently the most prevalent binder in underground backfill mining methods, primarily due to its established performance, yet it presents opportunities for significant cost optimization. Consequently, in this study, OPC was employed as the benchmark cementitious material for the control group. Guided by the principle of strength equivalence [30,31], the primary objective was to assess the viability of substituting OPC-based binders (at a low tailing-to-cement ratio, TCR) with the novel CP binder at a higher TCR. To simulate realistic field applications, all experiments were conducted based on the operational parameters of the Wushan Copper Mine, specifically a filling slurry solid content (SC) of 73%. Therefore, a comprehensive comparative investigation was undertaken to analyze the UCS of various CTB samples. This analysis included tailing–OPC mixtures with TCRs of 4 and 8, and tailing–CP mixtures with TCRs ranging from 6 to 16. It is important to note that a consistent curing age (CA) schedule of 1, 3, 7, 14, and 28 days was applied across all experimental scenarios. The results of this comparative UCS analysis for both tailing–OPC and tailing–CP samples are systematically presented in Figure 4.

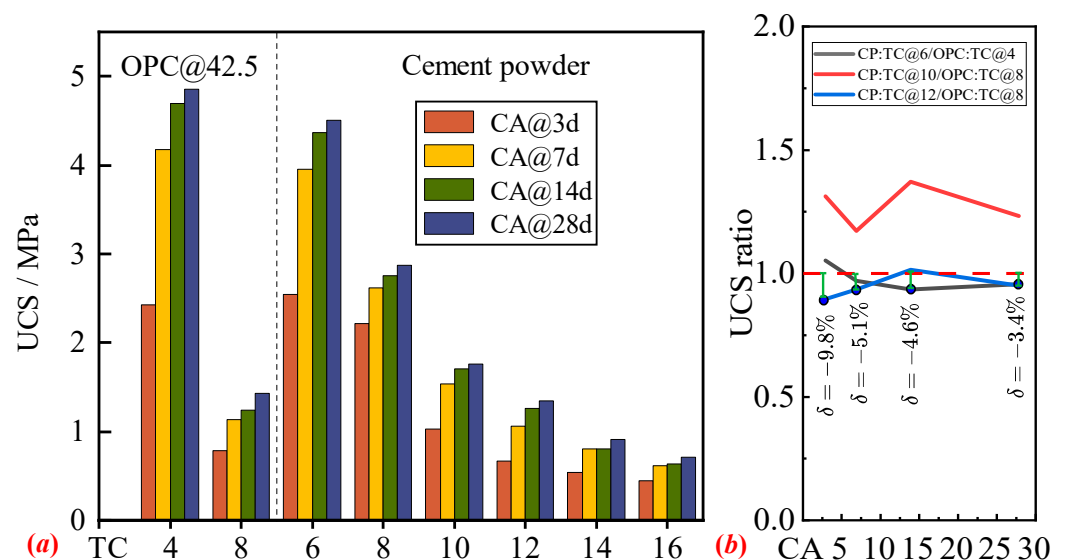


Figure 4. Performance comparison between the tailing–OPC and tailing–CP CTB samples. (a) Determined UCS of tailing–OPC and tailing–CP CTB samples with SC@73%, and (b) UCS ratio with various TCR schemes.

The findings reveal that the tailing–CP CTB, featuring a TCR of 6, presents a strength attenuation characteristic during the intermediate and late stages compared to the tailing–OPC CTB, which possesses a TCR of 4. However, the degree of attenuation is

minimal, falling below 5%, and the UCS surpasses 4 MPa after 28 days of curing (Figure 4b), satisfying the necessary bearing capacity for mining-related activities. Furthermore, using tailing–CP CTB (with the lowest UCS ratio of 1.2 in Figure 4b) with a TCR of 10, instead of tailing–OPC CTB with a TCR of 8, has clearly demonstrated superiority in achieving the desired design strength. To further investigate the potential of CP material to enhance the strength of CTB, the feasibility of tailing–CP CTB with a TCR of 12 as a substitute for tailing–OPC CTB with a TCR of 8 was analyzed. The results indicate that the strength attenuation does not surpass 5.1% within 3 d and above curing age, which corroborates the effectiveness of such alternatives under less demanding UCS conditions. Based on the preceding analysis, it can be concluded that CP materials significantly enhance the strength of CTB and may be used as a substitute for OPC materials, thereby achieving cost savings from an engineering perspective.

3.2. Strength Characteristics of CTB

Within the context of mining practice, the mechanical properties of CTB are primarily characterized by its UCS, owing to its convenient testing protocol and the intuitive nature of the results [1,22,34]. The UCS of CTB is affected by several factors, including SC, CA, and TCR. Figure 4 summarizes the impact of CA and TCR on the UCS of tailings–CP CTB with varying SC (71%, 72%, 73%, and 74%).

The UCS of CTB is governed by solid content (SC), curing age (CA), and tailing-to-cement ratio (TCR), as illustrated in Figure 5. The results indicate that TCR and CA are the dominant factors, while SC exerts a comparatively minor effect within the tested range. Specifically, UCS is inversely related to TCR, with the strength enhancement being most pronounced at TCR values below 8 and becoming more gradual for TCRs greater than 10 (Figure 6). Concurrently, UCS increases monotonically with CA. This development is characterized by a rapid strength gain during the early curing stages (≤ 7 days), which subsequently plateaus in the intermediate to late stages (≥ 14 days). This behavior is attributable to the formation of a denser pore structure from more extensive hydration reactions, facilitated by higher binder proportions (lower TCR) and prolonged curing [2,16,22,29,38,42].

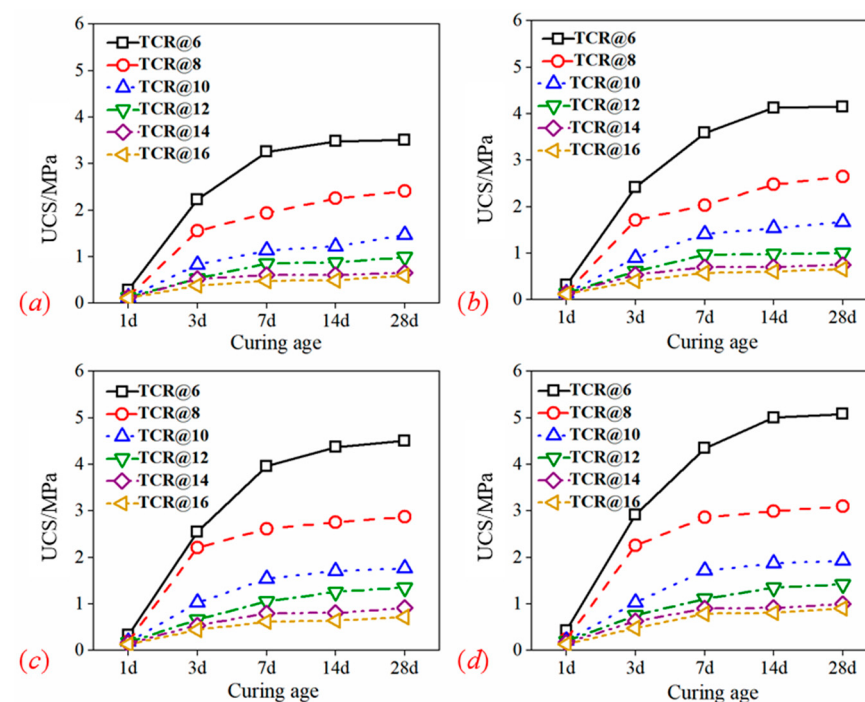


Figure 5. Effects of CA and TCR on UCS evolution behavior of CTB with SC of (a) 71%, (b) 72%, (c) 73%, and (d) 74%, respectively.

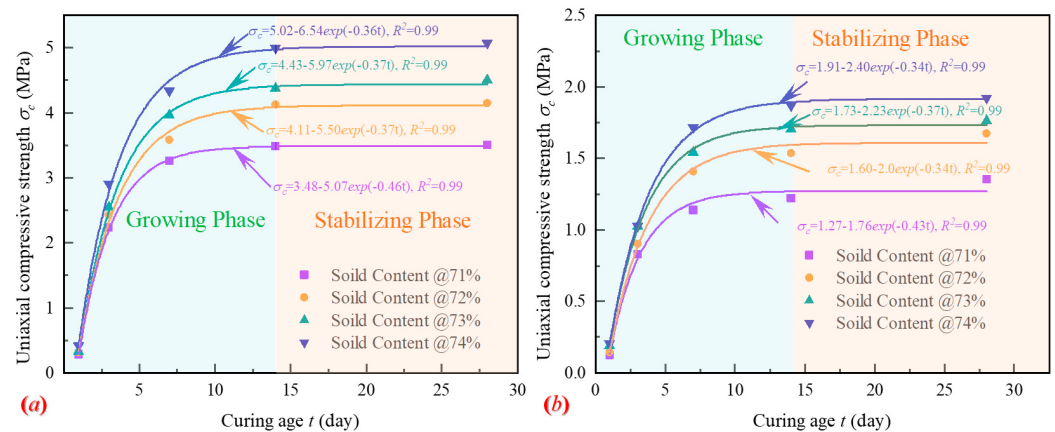


Figure 6. Evolution characteristics of UCS with SC and CA at TCR of (a) 6 and (b) 10, respectively.

Notably, the functional form of the UCS evolution with CA is mainly independent of SC and TCR and can be accurately represented by a unified exponential function:

$$\sigma_c = a + b \exp(-\alpha t) \quad (1)$$

where a , b , and α are the constant coefficients, and t represents the CA variable.

To better characterize the growth pattern of UCS at 28 days of curing, a strength increase factor k is defined and expressed as follows:

$$k = \sigma_{28d} / \sigma_{1d} \quad (2)$$

where σ_{28d} and σ_{1d} represent the UCS of CTB at 1 day and 28 days, respectively.

Figure 7 illustrates the impact of SC and TCR on the strength growth factor of CTB. The results indicate that the strength-increasing factor k initially increases and then decreases as the TCR increases. Notably, when the TCR is 8, the strength increasing factor for CTB with SC of 71%, 72%, 73%, and 74% reached 17.84, 18.23, 15.35, and 12.79, respectively. Additionally, the results indicate that the strength-increasing factor tends to stabilize as the TCR exceeds 12, implying that using a higher TCR to enhance the UCS is no longer significant.

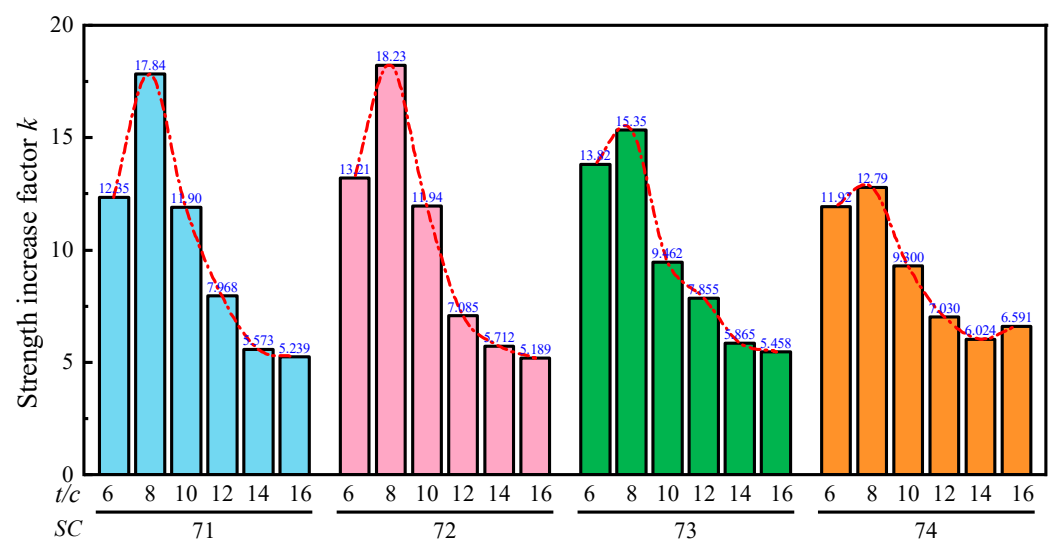


Figure 7. Effect of SC (71%, 72%, 73%, and 74%) and TCR (6, 8, 10, 12, 14, and 16) on strength increase factor of CTB.

3.3. Behavior of Stress–Strain Curves

Stress–strain curves reflect the characteristic deformation behavior and the ultimate load-bearing capacity of the CTB material. A summary of the stress–strain curves, controlled by the parameters of CA, SC, and TCR, is provided in Figure 8. In general, these curves can be segmented into four principal stages, using the curves in Figure 8a for illustrative purposes: (1) Initial Compaction (OA section): At the onset of loading, the internal pore structure of the CTB experiences progressive compaction, which manifests as a concave nonlinear growth feature in the stress–strain curve. (2) Linear Elastic Deformation (AB section): Once compacted, the specimens enter a phase of recoverable elastic deformation when subjected to external loading, as observed in the AB section. It is worth noting that a characteristic linear growth pattern is typical for specimens with a relatively homogeneous structure, whereas a multimodal nonlinear growth may be exhibited by specimens with heterogeneous structures. (3) Nonlinear Hardening and Crack Propagation (BC section): This stage is commonly associated with the unstable failure process. During this phase, the stress–strain curve becomes nonlinear. It gradually transitions into a convex-shaped nonlinear curve. This continues until the material reaches its peak stress. Microcracks are primarily initiated in the weakest regions of the CTB structure and proceed to evolve, develop, and propagate unstably as the applied load increases. For highly compliant CTB specimens, the stress–strain curve in this region may display a distinct plastic yield characteristic with minimal or slow strain increase. (4) Crack Acceleration and Softening (CD section): In the post-peak region, the sample’s stress-carrying capacity gradually diminishes as strain increases. This softening is due to the accelerated expansion of internal cracks, which can evolve into macroscopic fractures spanning the entire sample.

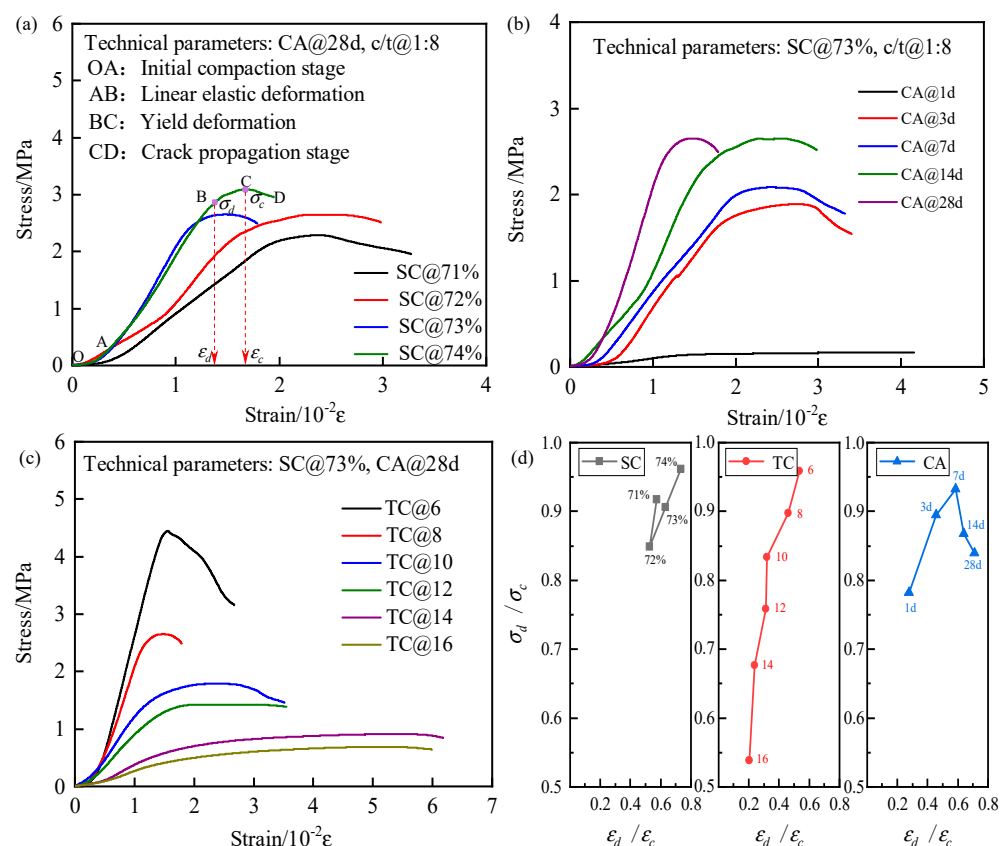


Figure 8. Effect of (a) CA, (b) SC, and (c) TCR on stress–strain curves and (d) critical physical parameters of CTB.

When comparing the impact of multiple factors on the morphology of the stress–strain curve, the alteration of the curve type remained indistinct within the narrow control range of SC (71–74%). However, the influence of CA and TCR on the transformation of this behavior was more pronounced. For instance, at a curing age of just 1 day, the stress–strain response exhibited typical plastic yield properties. As the curing period progressed, a post-peak strain softening characteristic became more evident. At a 3-day curing age, the stress–strain curve exhibited a stable pattern of change, although its maximum strength was still capable of further enhancement. The impact of TCR on the curve was more prominent than that of SC or CA. With an increasing TCR, the stress–strain curve progressively shifted from a strain-softening behavior to a yield flow-softening response, ultimately leading to persistent plastic yield characteristics. Figure 8d presents a comparison of the influence of the control parameters SC, TCR, and CA on normalized damage stress (σ_d/σ_c). These results show that SC and CA display opposing nonlinear effects on this parameter, whereas the impact of TCR is nearly linear.

Drawing from the stress–strain curve results illustrated in Figure 8, the impact of the CA, SC, and TCR on the elastic modulus is presented in Figure 9. The findings reveal that both CA and SC exert a favorable influence on the enhancement of the elastic modulus. Conversely, the TCR exerts a deleterious effect on the elastic modulus, causing a decayed trend as the TCR increases. An in-depth examination of the correlation between elastic modulus E and UCS σ_c is undertaken based on the preliminary findings presented in Figure 5. This analysis is visualized in Figure 10 by depicting both the empirical data and corresponding fitting curves. It is discerned from these results that the intersection points between elastic modulus E and σ_c is roughly located between fitting curve $E = 117.6\sigma_c + 8.3$ and $E = 56.7\sigma_c + 3.2$.

3.4. Failure Mode

Given that CTB is a synthetic material comprising multiple components, its macroscopic failure mode is subject to the influence of various factors. This is exemplified in Figure 11, which provides a comparative and analytical representation of the macroscopic failure modes of CTB samples subjected to uniaxial compression. The figure details the behavior of a CTB with an SC of 73% across different curing ages, specifically for TCRs of 6 and 16. The observations reveal that the macroscopic failure mechanism of the CTB specimens is predominantly influenced by the development of macroscopic tensile cracks, while the effect of macroscopic shear cracks represents a secondary factor. It was also determined that curing age significantly influences the macroscopic failure mode more than the tailing-to-cement ratio. To illustrate, for curing ages of 3 days or less, CTB samples with a TCR of 6 displayed only a limited number of visible cracks propagating along the sidewall, as shown in Figure 11a. In a similar manner, for the CTB sample with a TCR of 16, the macroscopic cracks propagated solely along a unidirectional plane, as depicted in Figure 11b. This phenomenon is principally attributed to the low inherent strength of the CTB at early ages, which results in bulging deformation during the loading process. Nevertheless, the distribution pattern of macroscopic failure cracks in CTB specimens with a low TCR became progressively more complex as the curing age advanced. Specifically, the cracks were predominantly macroscopic tensile cracks that traversed the entire specimen, manifesting as an axial splitting failure. However, in CTB specimens with a high TCR, the macroscopic failure surface was composed of tensile and shear cracks and ran through the entire specimen in a mode approximating shear failure.

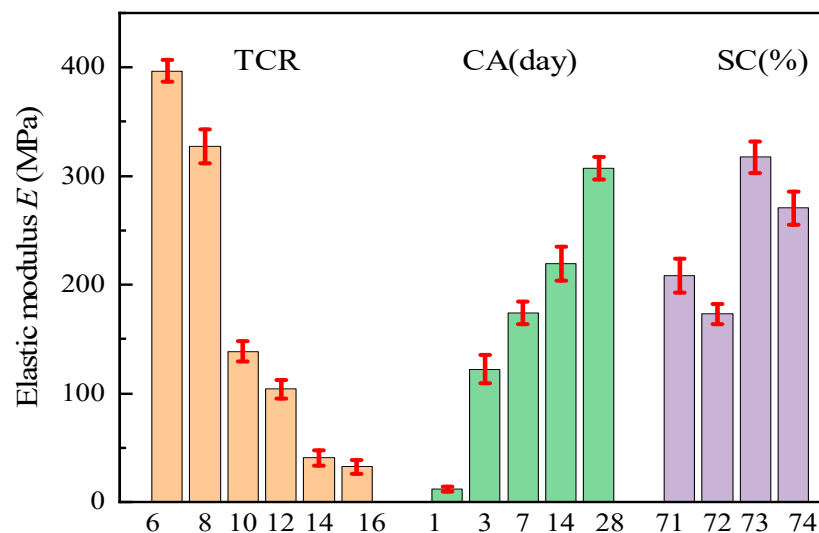


Figure 9. Effect of TCR, CA, and SC on the elastic modulus of CTB.

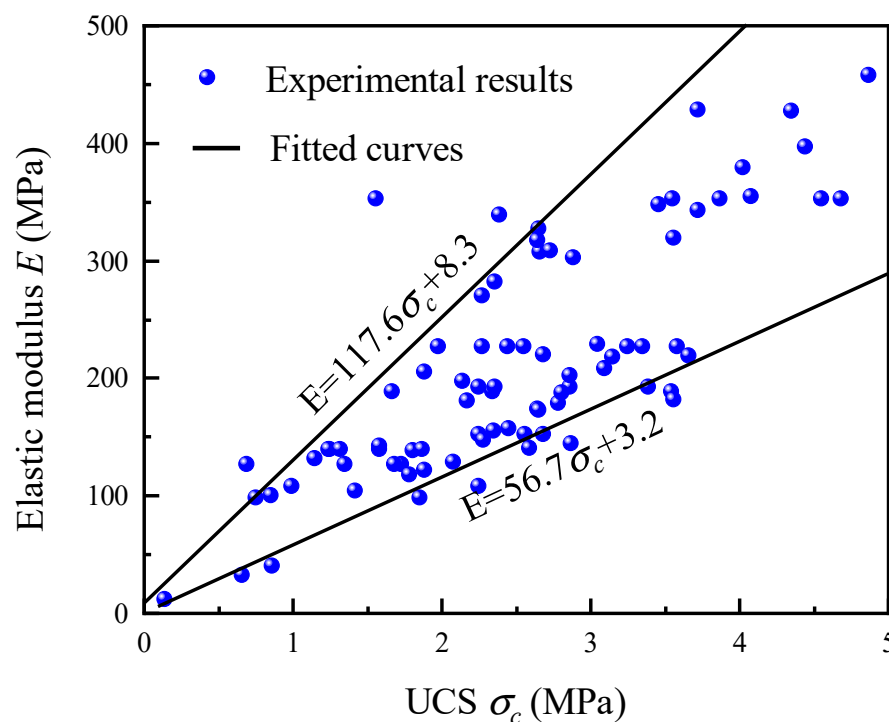


Figure 10. Correlation between modulus of elasticity and UCS.

3.5. Microanalysis of Enhancement Mechanism of UCS

Microscopically, the mechanical characteristics of CTB depend on its internal structure. This structure consists of two main components. The first is the core skeleton, a grid formed by the bonding of aggregate particles and cementitious materials. The second is the micro-defective structure, which includes micro-pores, voids, and micro-cracks [16,22,29,43,44]. Simultaneously, the SEM results play a significant role in interpreting the hydration reaction behavior of CTB and revealing the influence of microstructure characteristics on the strength enhancement mechanism of CTB [5,29,30,36,42,45]. In this work, several fragments were selected from the best performing CTB samples undergoing uniaxial compressive failure for microstructural analysis. The effects of diverse influencing factors (such as TCR, SC, or CA) on the hydration reaction behavior of CTB are investigated. Accordingly, a clear internal correlation is explained by the hydration reaction characteristics and the microscopic-scale progression of UCS.

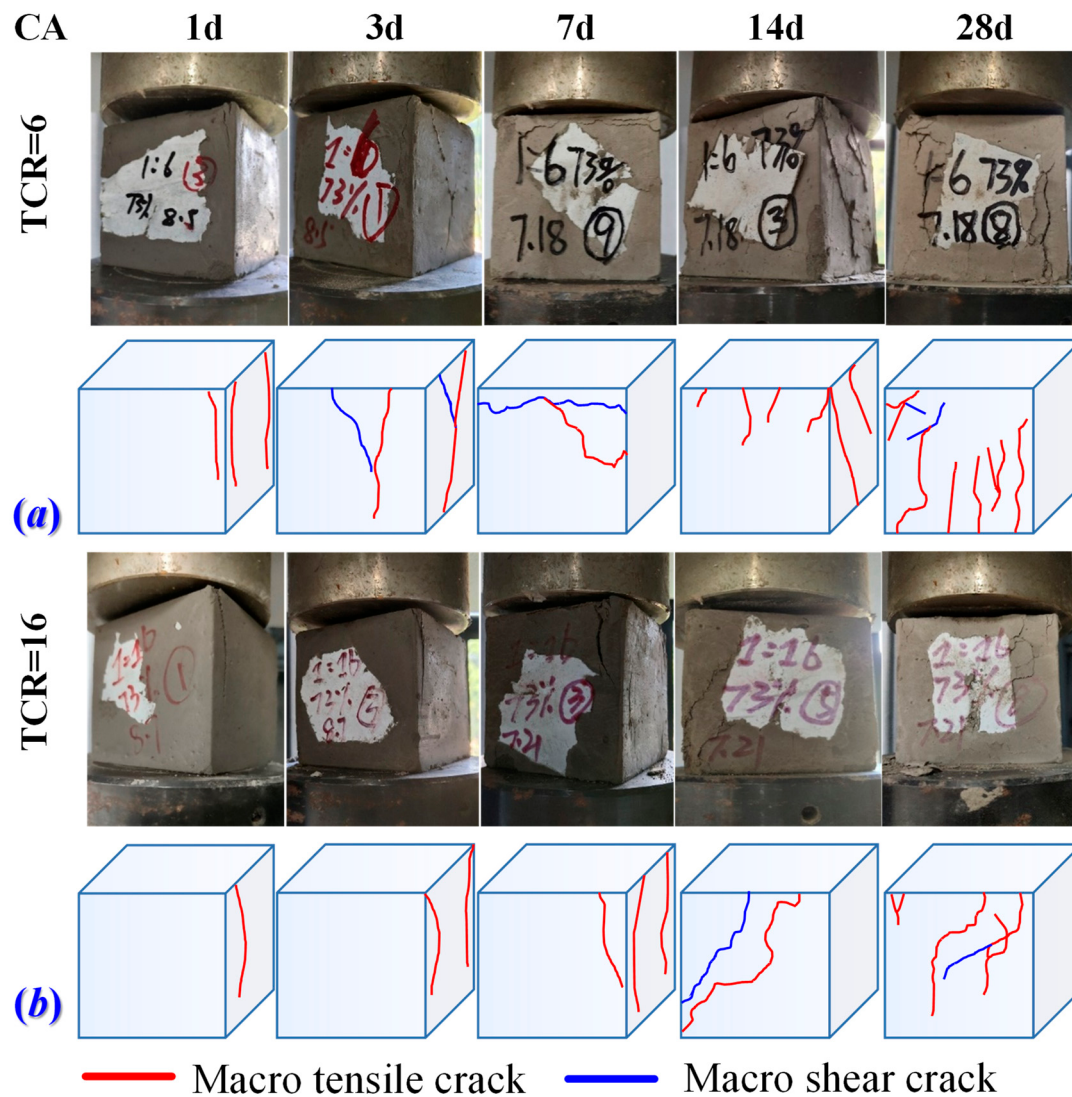


Figure 11. Failure modes of uniaxial compression for CTB with an SC of 73% at various CA schemes: (a) TCR = 6; (b) TCR = 16.

(a) General characteristics of CTB microstructure

The SEM microstructure of CTB fragments, observed at various magnifications, is illustrated in Figure 12. The examined fragments were derived from the failed CTB samples prepared with an SC of 73% and a TCR of 6 and cured for 28 days. The results indicate that, upon examination at $500\times$ magnification, the 28-day cured samples possess what appears to be a consistent and compact microstructure. However, upon closer inspection at higher resolutions (as shown in Figure 12b–d), it becomes apparent that this seemingly uniform and dense structure comprises a variety of substructures. These include a gelatinous mass, tailing particles, pores, and voids, forming a porous, honeycomb-like structure. This finding agrees with previous research [24,29,36]. The primary formation of these porous structures can be attributed to the spatial arrangement and intergrowth of hydration products, such as amorphous and flocculent C-S-H gels and needle-like ettringite, which are generated during the hydration process. It is particularly noteworthy that these hydration products encapsulate the adjacent tailing particles and intertwine with the nearby loose tailing materials. This action creates a solid and cohesive coarse aggregate through bonding effects, reducing porosity and improving the strength of the microstructural skeleton inside the CTB samples. This observation explains the inherent mechanism of compressive strength

development in the backfill material from a microscopic perspective, facilitating a better understanding of the material's macroscopic properties.

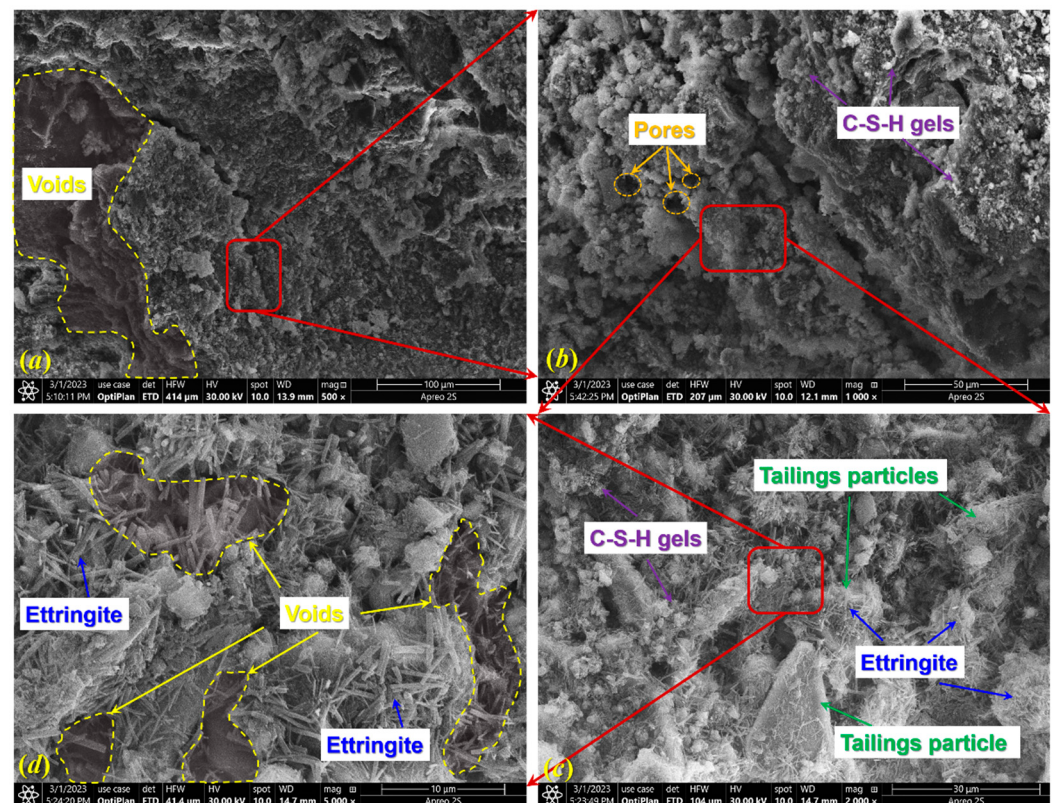


Figure 12. Microstructure morphology of a 28-day cured CTB sample with an SC of 73% and a TCR of 6 at the magnification of (a) 500 $\times$, (b) 1000 $\times$, (c) 2000 $\times$, and (d) 5000 $\times$, respectively.

(b) Influence of TCR

Figure 13 exemplifies the microstructural features of CTB fragments prepared with a solid content (SC) of 73% and cured for 28 days. A comparative analysis of the SEM microstructure and morphology was conducted at tailing-to-cement ratios (TCRs) of 6 and 12, with representative magnifications of 500 $\times$ and 2000 $\times$ selected for each TCR condition. The results revealed that the microstructure of the CTB samples with a low TCR of 6 exhibited a relatively dense and homogeneous overall appearance (Figure 13a,b). Furthermore, the tailing particles were observed to be agglomerated by the nucleating action of the C-S-H gel, consequently forming the essential load-bearing skeleton of the microstructure. It should be noted that the primary skeleton contains interstitial spaces. Finer, dispersed tailing particles reside in these spaces. Over time, the crystalline growth of C-S-H gel and ettringite progressively binds these fine particles together. This process establishes durable force chains that are integral to the stress-bearing core of the skeleton [27,44]. This infilling behavior fills void spaces and densifies the core skeleton's network structure, which naturally translates to superior macroscopic mechanical properties and higher strength. Conversely, when the TCR was increased to 12, the microstructure of the CTB samples became significantly more intricate and less consolidated.

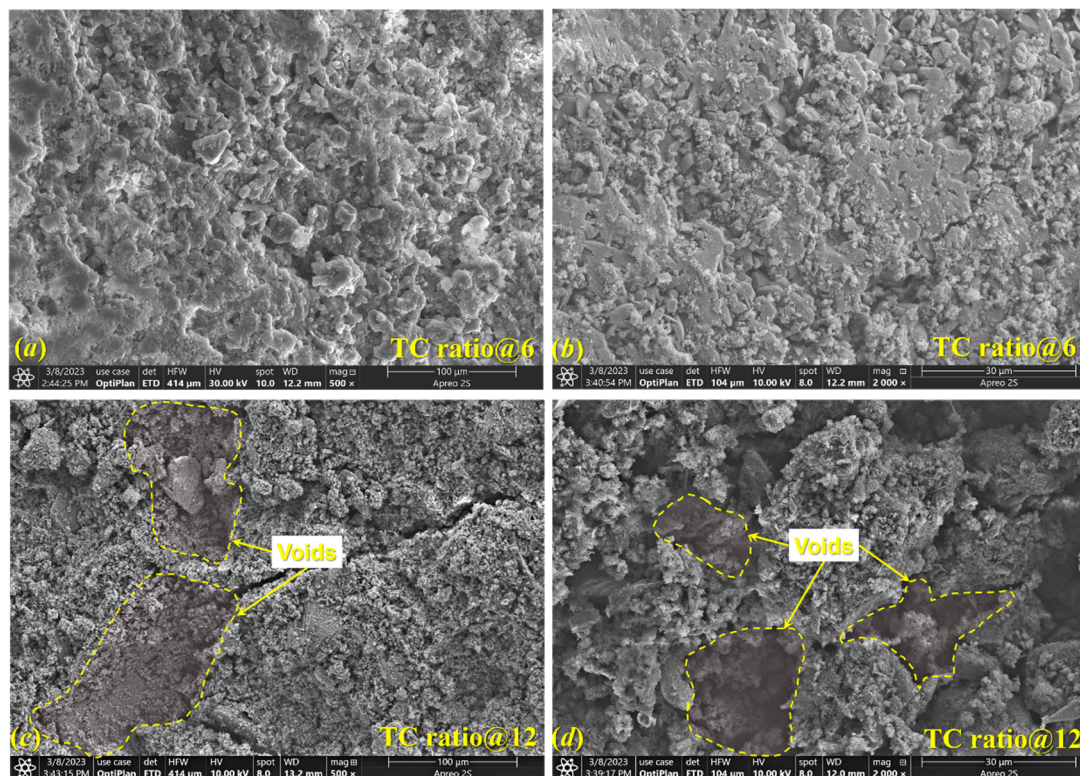


Figure 13. Surface morphology of 28-day cured CTB samples at the SC 73% with a TCR of 6 (a,b) and 12 (c,d), respectively.

In contrast to the dense microstructure observed at a TCR of 6, the samples at a TCR of 12 (Figure 13c,d) exhibited a more heterogeneous and porous cavity structure, with voids of diverse scales densely distributed throughout the matrix. Although a significant proportion of the tailing's particles were enveloped by a flocculent C-S-H gel, forming a polymeric mass, this resulting matrix lacked compactness and remained relatively loose. Upon further examination, it was determined that certain tailing particles clustered together to create small, secondary aggregates. These weakly bound aggregates appeared to attach themselves to the primary morphological structure in an isolated manner, failing to achieve adequate adhesion. Consequently, from a macroscopic loading perspective, such a poorly integrated structure is susceptible to the misalignment and slippage of these aggregates under stress, which would ultimately contribute to a reduction in the overall mechanical strength of the CTB.

(c) Influence of solid content

The influence of SC on the microstructure is illustrated in Figure 14, which displays micrographs of a CTB with a 28-day curing age and a TCR of 8, prepared at SCs of 71%, 72%, 73%, and 74%, respectively. The results consistently show that the micromorphology of the CTB is characterized by an incompletely formed, porous structure, with voids scattered in a disordered arrangement throughout the entire matrix space. Further observation confirms that this structure is primarily composed of C-S-H gel, pores, and embedded tailing particles. Notably, despite the increase in SC from 71% to 74%, there was no discernible variation in the overall compactness or fabric of the microstructural matrix. Therefore, it can be reasonably inferred that minor fluctuations in the SC of the CTB, under otherwise identical technical parameters, would not have a significant impact on the overall microstructure and morphology of the resulting CTB fragments.

(d) Influence of curing age

Numerous studies have established that curing age is a critical factor that significantly affects the microstructure and morphological characteristics of CTB [2,19,26,39,42]. To investigate this evolution, a comparison of the microstructure matrix at different curing stages—specifically 3, 7, 14, and 28 days—is presented in Figure 15.

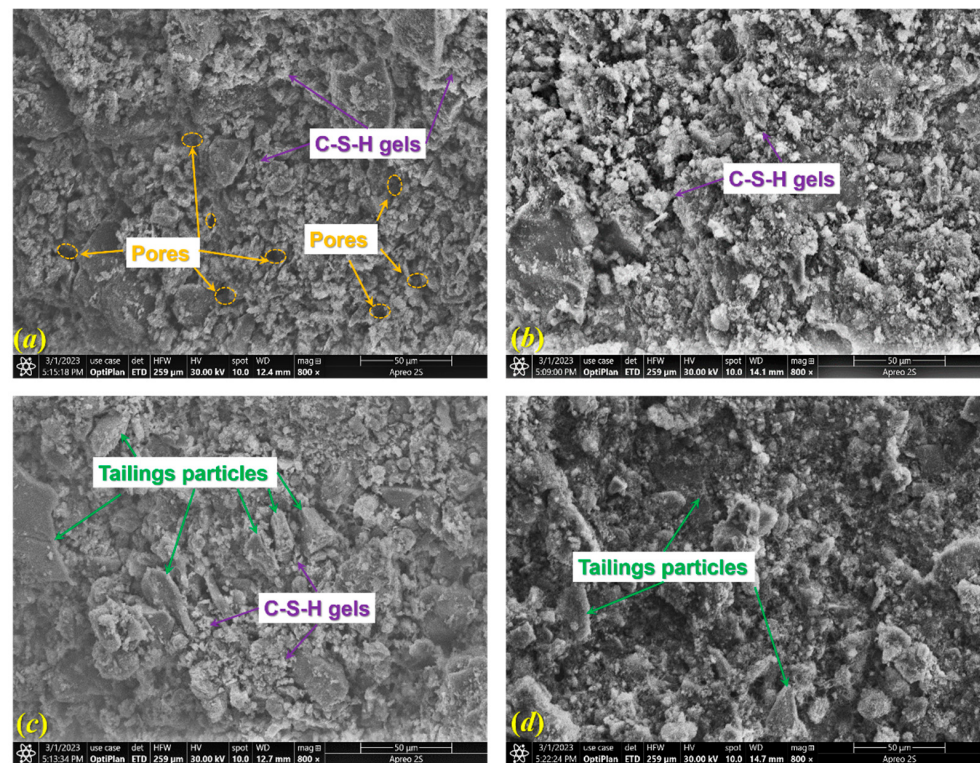


Figure 14. Surface morphology of 28-day cured CTB samples with TCR of 8 at SC of (a) 71%, (b) 72%, (c) 73%, and (d) 74%, respectively.

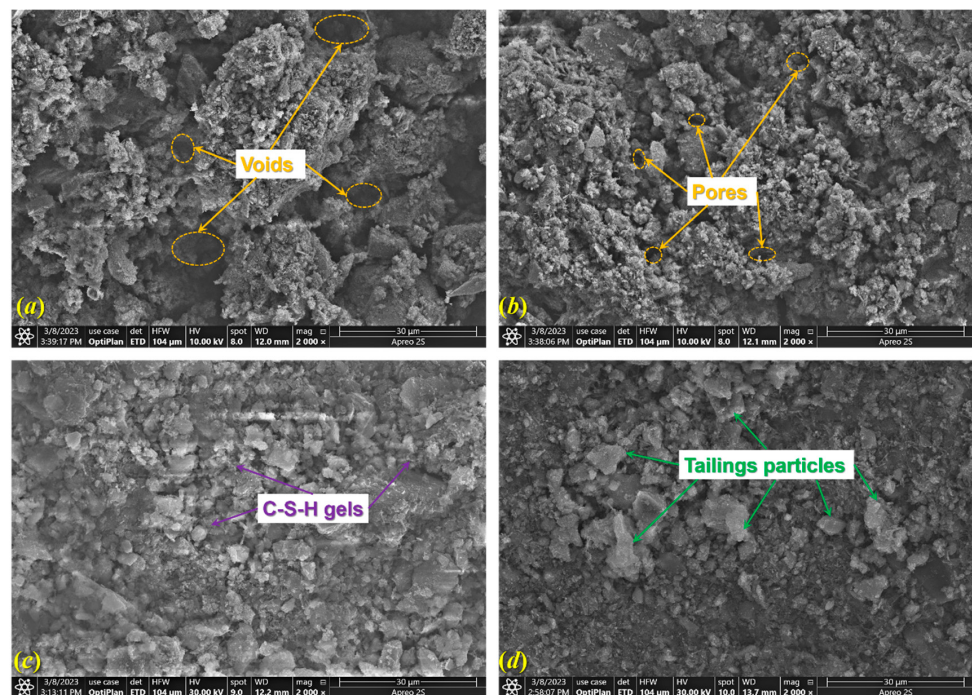


Figure 15. The microstructure of the CTB with a TCR of 8 and an SC of 73% after (a) 3 days of curing, (b) 7 days of curing, (c) 14 days of curing, and (d) 28 days of curing, respectively.

At the early 3-day curing stage, the initial formation of a distinct network framework was observed. This nascent structure was primarily composed of early-stage hydration products, including short, rod-like ettringite crystals and amorphous Calcium-Silicate-Hydrate (C-S-H) gel (Figure 15a). However, at this point, the framework remained underdeveloped, and the surrounding matrix contained numerous voids, exhibiting a typically loose and porous character. Such a loosely consolidated microstructure is responsible for the characteristically low early-age strength due to insufficient hydration [1,2,26,29]. The ettringite crystals coarsen and intertwine with the proliferating C-S-H gel as hydration progresses to the 7-day and 14-day curing stages (Figure 15b,c). This synergistic growth process leads to a more robust, interconnected mesh-like skeletal structure [46] and enhances the cohesive bond strength among the tailing particles [47]. By the 28-day curing mark, the volume of hydration products had continued to increase substantially. This ongoing process gradually infilled and refined most of the pores and voids within the matrix, ultimately yielding a significantly denser and more homogeneous composite matrix encapsulating the tailing particles (Figure 15d). These progressive structural changes underscore the fundamental principle that the continuous formation and maturation of hydration products play a pivotal role in the long-term strength evolution of the material.

4. Conclusions

In this work, a novel cementitious powder based on alkali-activated slag is developed, and its application potential is systematically validated as a substitute for OPC in CTB. The main conclusions are as follows:

- (1) The novel CP binder proved to be an effective replacement for OPC. At a solid content of 73%, the CTB prepared with CP at a TCR of 10 or 12 exhibited compressive strength after 28 days (2.6~2.8 MPa) comparable to or higher than that of the OPC-based counterpart with a TCR of 8 (~2.5 MPa). This represents a 33% reduction in binder dosage without sacrificing performance.
- (2) TCR and CA predominantly controlled the mechanical performance of the CTB, while the effect of SC was negligible within the 71–74% range. The UCS increased exponentially with decreasing TCR and increasing CA, showing rapid early-age (≤ 7 days) strength gain before stabilizing. The stress–strain response evolved from plastic yielding at early ages to a brittle, strain-softening behavior with extended curing.
- (3) The CTB specimens primarily failed due to tensile splitting accompanied by secondary shear cracks. As the curing age increased and the TCR decreased, the internal structural integrity improved, resulting in a more intricate crack network at failure. This indicates a transition from a weak, ductile body to a firm, brittle solid.
- (4) The improvement in macroscopic mechanical properties stemmed from continuous microstructural optimization. Hydration of CP produced an abundant network of products with morphologies characteristic of amorphous C-S-H gel and needle-like ettringite, which filled inter-particle voids, cementing and encapsulating tailings into a dense, interlocked skeleton. A lower TCR (i.e., higher binder content) and longer curing age promoted more complete hydration, yielding a more integrated, less porous microstructure and thus higher macroscopic strength of the CTB.

This study confirms that the developed slag-based binder is a promising solution for producing high-performance, low-cost, and eco-friendly cemented tailing backfill, offering both a solid theoretical basis and a practical pathway for mining solid waste utilization and green mining development.

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Abbreviations

Cementitious powder	CP
Solid content	SC
Tailing-to-cement ratio	TCR
Curing age	CA
Cemented tailing backfill	CTB
Ordinary Portland cement	OPC
Grain size distribution	GSD
Full tailings	FT

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