

Article

Strength Behavior, Fracture Evolution, and Energy Dissipation Properties of Cemented Tailings Backfill in Chemical Environment

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Abstract

With the growing depth of underground mining, issues surrounding solid waste storage and the effective use of mine water have become pivotal to achieving sustainable mining practices. The complex ionic composition of mine water impacts the performance of traditional cemented tailings backfill (CTB) materials. Gold mine tailings, combined with cement, were repurposed as the cornerstone raw materials in this investigation. Solutions with identical target concentration gradients for Cl^- , SO_4^{2-} , and HCO_3^- were prepared separately using NaCl , Na_2SO_4 , and NaHCO_3 , respectively, with each salt dosed to achieve the desired anion concentration. These solutions served as mixing water for preparing samples with tailings and cement. Strength, energy dissipation characteristics, and microstructure of CTB were investigated by single-axis compression test, XRD, and SEM-EDS analysis. Experimental results demonstrate that adding three reagents— NaCl , Na_2SO_4 , and NaHCO_3 (covering Cl^- , SO_4^{2-} , and HCO_3^- ions, respectively)—at appropriate concentrations enhances mechanical properties. At their optimum concentrations, these salts increased the compressive strength of CTB by approximately 30%, reaching ~4 MPa. However, further increases in salt concentration produced inconsistent strength responses, with bicarbonate-containing mixtures exhibiting the most pronounced strength reduction. These effects are primarily attributed to competition between the introduced anions and cement hydration reactions, which alters the pore structure and consequently the density and strength of the hardened matrix. Incorporating different ion-covering backfill at appropriate concentrations enhances mechanical strength. These findings provide new opportunities for CTB mix design and mine water utilization. However, as this study considered only single-ion systems, further investigation is needed to elucidate the combined effects of multiple ions present in actual mine water.

Keywords: cemented tail backfill; strength; fracture; chemical exposure; microstructure

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1. Introduction

As a vital base for gold and polymetallic mineral resources in China [1,2], mining activities on the Jiaodong Peninsula generate substantial economic value [3,4] while also producing massive quantities of solid mining waste, along with highly mineralized mine

water [5–7]. Traditional disposal methods such as surface stockpiling and direct discharge consume terrestrial resources, posing ecological and safety hazards [8–10]. As an unavoidable non-conventional water resource generated during mining operations, mine water has become a core issue in mines' green development [11]. The direct discharge of large volumes of mine water may disrupt regional water ecosystems [12]. Mixing tailings with cementitious materials to form cemented backfill for underground goaf filling represents a key technology that concurrently addresses solid waste disposal [13,14], rock mass control [15], and surface protection [16,17]. Mine water exhibits complex chemical composition [18]. Existing geochemical studies in the region indicate that its mineralizing fluids and related groundwater contain Cl^- and SO_4^{2-} anions, accompanied by minor bicarbonate ions, while cations are dominated by Na^+ and K^+ , resulting in highly mineralized mine water [19]. If backfills covering Cl^- , SO_4^{2-} , and HCO_3^- are directly prepared, they will undergo complex chemical reactions with added cementitious materials (ordinary Portland cement), thereby affecting the hydration process, microstructure, and macroscopic mechanical properties.

To enhance the early strength of cemented backfill, chloride- and sulfate-based additives, along with other early-strength agents, are commonly incorporated [20–26]. While chloride ingress is a major cause of corrosion and long-term deterioration in reinforced concrete [27–30], its role in non-reinforced cemented backfill is fundamentally different. Recent studies have elucidated the underlying hydration mechanisms, including C–S–H nucleation and growth [31], the competitive formation of AFt and AFm phases under ion-rich conditions [32], and the regulatory effects of anions on early hydration kinetics [33]. These insights provide a mechanistic basis for linking ionic composition to the microstructural evolution and macroscopic mechanical performance of cemented backfill.

Regarding chloride and sulfate ions, Zhu et al. [34] found that chloride ions did not induce the creation of new hydration crops, with the matrix still dominated by AFt and C–S–H. Grout's strength enhancement was achieved by endorsing hydration crops' creation and optimizing grout structure. Chen et al. [35] identified that the interplay between pore volume and the concentrations of C–S–H, AFt, and Friedel's salt is concrete strength's critical determinant. Zhao et al. [36] verified that a proper chlorine content (6.9%) in washed fly ash, achieved by regulating the competitive creation of AFt and Friedel's salt, optimized C–(A)–S–H gel's structure and openly enhanced binder's macroscopic properties. Teng et al. [37] and Lu et al. [38] proved that triethanolamine enhances the ability of systems having high fly ash content to bind chloride ions, increases hydration level, and effectively advances grout's strength. Al-Moselley and Fall [39] found that sulfates retarded the early strength development of grout by inhibiting the cement hydration process. Wang et al. [40] found that externally applied sulfates enhance the short-term strength of grout bodies by promoting hydration crops' creation. However, over the long term, gypsum growth leads to volume expansion and microstructural degradation, thereby reducing strength. Min et al. [41] and Cui et al. [42] report that sulfates inhibit the hydration of ordinary Portland cement, but, over time, they promote matrix densification and fiber confinement, thereby enhancing strength. Conversely, sulfates boost aluminate cement's hydration, which respectively reduces and increases matrix strength. Guo et al. [43] demonstrated that under the coupled action of loading and sulfates, an appropriate stress level ($\leq 60\%$) can compact pores, inhibit sulfate intrusion and calcium aluminate hydrate expansion, thereby delaying deterioration. The sodium bicarbonate ion can alter the composition, accelerate C3S's hydration, and promote AFt's alteration to AFm, thereby accelerating the hydration process and enhancing early strength [44].

Unlike chloride and sulfate, bicarbonate primarily affects early-stage hydration and pore structure evolution, thereby controlling matrix densification. He et al. [45] discovered that bicarbonate ions boost the early alkaline environment of CHSTF, accelerating

hydration reactions, stabilizing the sulfate phase, and causing Ca carbonate to fill pores, thereby improving early strength. Seo et al. [46] and Wang et al. [47] confirmed that bicarbonate ions permeate into the cement matrix, consuming calcium hydroxide and forming calcium carbonate precipitates. This quickens cement clinker's hydration reaction and effectively enhances the cement matrix's strength. Wang et al. [48] discovered that the reaction between bicarbonate ions and calcium hydroxide leads to calcium carbonate precipitation, which promotes the creation of calcium aluminate hydrates and improves cement's early hydration rate. This effectively increases the early strength of the backfill.

Despite these advances, existing studies have rarely incorporated the physico-mineralogical characteristics of typical Jiaodong tailings by employing them as the aggregate phase in systematic investigations. This implies that research findings may not be applicable to exploring CTB performance. The focus has been on evaluating the macro-properties of backfill materials affected by mine water or solely examining the impact of individual ions (Cl^-). Systematic research on the concentration effects of characteristic anions in mine water (i.e., Cl^- , SO_4^{2-} , and HCO_3^-) remains lacking. Accordingly, the mechanisms by which these anions affect CTB performance, as well as their optimum concentrations in mixing water, remain poorly understood. Addressing this knowledge gap is critical for the rational use of highly mineralized mine water as CTB mixing water, enabling resource recovery while maintaining backfill quality and long-term stability.

This study will focus on simulating the core anion components of Jiaodong mine water, systematically examining single-anion environments using diverse concentration gradients of Cl^- , SO_4^{2-} , and HCO_3^- (prepared by dissolving NaCl , Na_2SO_4 , and NaHCO_3 into single-salt solutions of varying concentrations). A fraction of the cement-based product to tailings is secured to prepare and cure backfill specimens. By testing compressive strength and analyzing phase composition (XRD) and microstructure (SEM), the relationship between Cl^- , SO_4^{2-} , and HCO_3^- concentrations and the fill's macroscopic features and microstructure will be examined. This study represents the first systematic investigation to decouple and compare the concentration-dependent effects of Cl^- , SO_4^{2-} , and HCO_3^- in mixing water on the hydration, microstructure, and mechanical performance of CTB prepared with Jiaodong tailings. The findings provide a scientific basis for the safe and efficient use of mine water in sustainable backfilling. Nevertheless, because the experiments were conducted under single-anion conditions, further validation using multi-ion mine water is required before field implementation.

Beyond mechanical performance, the engineering applicability of CTB also depends on slurry workability, flowability, and pumpability. Previous studies have shown that dissolved ions and binder composition can substantially influence rheological behavior and hydration kinetics, thereby affecting slurry transport in underground operations [49]. However, the present study focuses on the microstructural mechanisms and strength evolution associated with individual anions. Consequently, rheological performance is beyond the scope of this work but represents an important direction for future investigations integrating coupled ionic, rheological, and mechanical effects.

2. Materials and Methods

2.1. Materials

Fills were constructed using gold mine tailings, Type 42.5 cement, deionized water, and three types of reagents. Shandong gold mine tailings were used to ensure that the experimental materials were representative of backfill conditions in the Jiaodong region. The binder was OPC 42.5R (Shandong Jiuqi Building Materials, Jinan City, Shandong Province, China), which was selected because it is the standard cement used in Jiaodong gold mine backfilling owing to its consistent quality, reliable strength development, and local availability, thereby enhancing the engineering relevance of the experimental results.

Before specimen preparation, the tailings were oven-dried at 100 °C for 12 h under forced-air circulation (Model 101-0, Shaoxing Super Instrument Co., Ltd., Shaoxing City, Zhejiang Province, China) to remove moisture. Upon completion of drying, gold mine tailings were promptly stored in airtight containers to minimize moisture absorption from ambient air. The particle size distributions of cement and gold mine tailings were broadly characterized. Physicochemical properties of tailings were systematically characterized (Figure 1), revealing a particle size distribution predominantly spanning 76–400 μm , with an average diameter (D_{50}) of 192 μm and a specific surface of 48.35 m^2/kg , ranking them as coarse tailings. The major oxide composition of gold mine tailings was determined using XRF spectrometry. The main oxide components identified were SiO_2 , Al_2O_3 , and K_2O , with respective contents of 74.70%, 13.10%, and 5.01%. XRD analysis indicates that the tailings consist primarily of SiO_2 , accompanied by minor amounts of potassium feldspar.

Figure 2 characterizes the physicochemical properties of cement. The cement particle size distribution is primarily concentrated between 0.96 μm and 120.27 μm , with $D_{10} = 2.70 \mu\text{m}$ and $D_{90} = 58.70 \mu\text{m}$. Cement's mean grain size (D_{50}) is 16.46 μm , and its specific surface is 0.84 m^2/kg . To determine cement's chemical composition, XRF was used to analyze its primary oxide constituents. The main oxides present in cement are CaO , SiO_2 , and Al_2O_3 , with respective contents of 55.71%, 23.86%, and 10.81%. XRD analysis indicates that cement's key constituents are calcium silicate and magnesium aluminate oxide phases, exhibiting favorable binding properties.

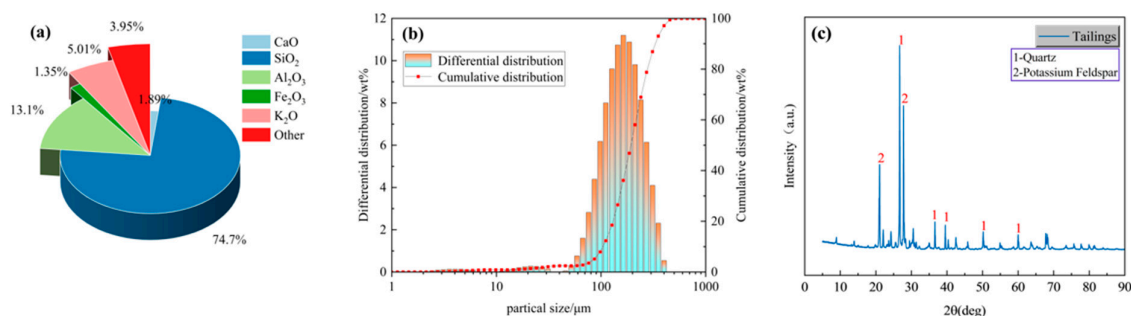


Figure 1. Tailings' features: (a) oxide; (b) gradation; and (c) mineralogical analyses.

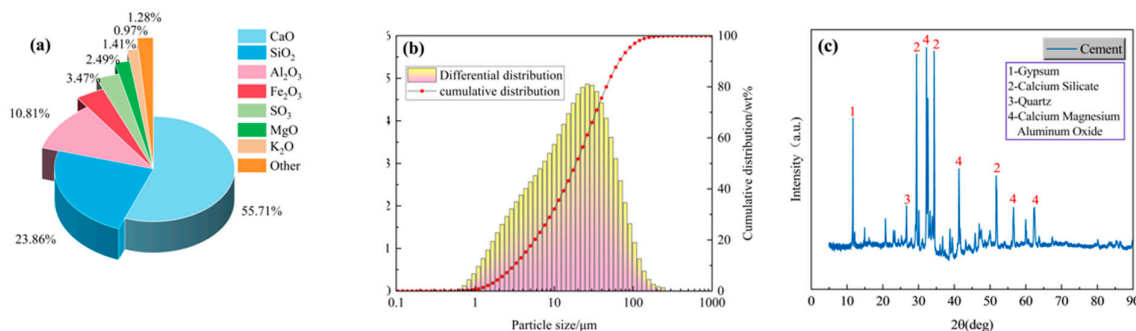


Figure 2. Cement's features: (a) oxide, (b) gradation, and (c) mineralogical analyses.

2.2. Sample Preparation

Table 1 summarizes the experimental program. The effects of anion type and concentration on the mechanical performance of CTB (cement-to-tailings ratio of 1:4, slurry concentration of 75 wt%) were investigated after 7 days of curing. Solutions with concentrations ranging from 2% to 10% were prepared by dissolving 6.67, 13.33, 20.00, 26.67, and 33.33 g of reagent, respectively, into the mixing water. Each specimen contained only one target anion, introduced via its corresponding sodium salt (NaCl , Na_2SO_4 , or NaHCO_3),

with the dosage calculated to achieve the prescribed concentration. Accordingly, the Cl^- , SO_4^{2-} , and HCO_3^- groups each represented single-anion systems. A witness group without added reagents was simultaneously launched to evaluate vagaries within strength properties of CTB following reagent addition. A precision balance (accuracy ± 0.01 g) was used to weigh the cement, reagents, tails, and mixing water. To minimize the impact of errors on the experimental results, three samples were prepared for each reagent at the same concentration, totaling 48 samples. The results are reported as the mean $\pm$ standard deviation (SD). For each mix, the average peak stress and corresponding SD were calculated from three replicate specimens.

Figure 3 presents the experimental workflow for CTB specimen preparation and characterization. Gold mine tailings, cement, and the designated NaCl , Na_2SO_4 , or NaHCO_3 solution were thoroughly mixed, cast into cylindrical molds, and cured under controlled conditions. The cured specimens were subsequently subjected to uniaxial compression testing to determine their mechanical properties, while their hydration products and microstructural characteristics were characterized by XRD and SEM-EDS analyses.

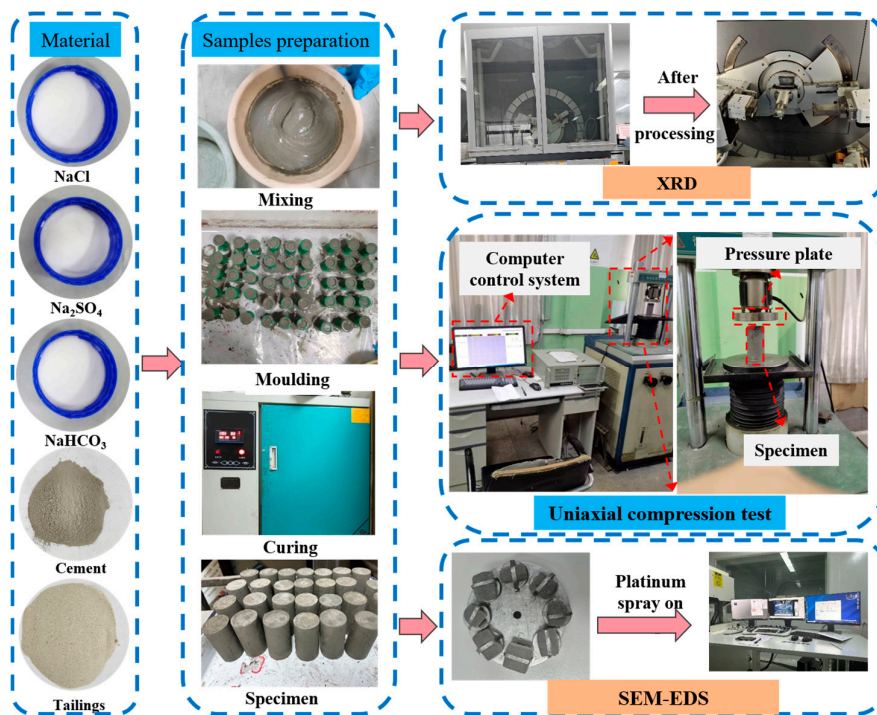


Figure 3. Sample preparation and preparation process.

Table 1. Mix proportions for ion tailings backfill at different concentrations.

Specimen ID	Reagent (g)	Cement (g)	Tailings (g)	Water (g)	Cement/Tail Ratio
None	0	200	800	333.33	1:4
Cl^- —2%	6.67	200	800	333.33	1:4
Cl^- —4%	13.33	200	800	333.33	1:4
Cl^- —6%	20.00	200	800	333.33	1:4
Cl^- —8%	26.67	200	800	333.33	1:4
Cl^- —10%	33.33	200	800	333.33	1:4
SO_4^{2-} —2%	6.67	200	800	333.33	1:4
SO_4^{2-} —4%	13.33	200	800	333.33	1:4
SO_4^{2-} —6%	20.00	200	800	333.33	1:4

SO ₄ ²⁻ —8%	26.67	200	800	333.33	1:4
SO ₄ ²⁻ —10%	33.33	200	800	333.33	1:4
HCO ₃ ⁻ —2%	6.67	200	800	333.33	1:4
HCO ₃ ⁻ —4%	13.33	200	800	333.33	1:4
HCO ₃ ⁻ —6%	20.00	200	800	333.33	1:4
HCO ₃ ⁻ —8%	26.67	200	800	333.33	1:4
HCO ₃ ⁻ —10%	33.33	200	800	333.33	1:4

2.3. UCS Testing

Filled specimens were exposed to uniaxial compression via a 150 kN PC-measured testing machine to assess their mechanical and damage characteristics. A control mix without salt addition within the mixing water was used to depict the net effects of salts within the appropriate CTB mixes. This equipment meets the loading requirements for filled specimens and is used to judge the effect of chemical reagents on the macroscopic mechanical properties of the specimens. The displacement control rate is set to 0.016 mm/s, and the force control rate is fixed at 0.5 kN/s. Before the experiment, we accurately recorded the height and diameter of the specimen. Simultaneously, we smoothed the top surface of the samples to be compressed using sandpaper to prevent stress concentration during loading, which could compromise data accuracy. A digital camera recorded the specimen's evolution at fixed points throughout uniaxial compression.

2.4. SEM-EDS Microanalysis

SEM is a key characterization technique for investigating the microstructure of cementitious materials, providing indispensable insights into the morphology and texture of cement, concrete, grout, and cemented tailings backfill. It is typically used in conjunction with EDS for determining elemental composition and concentration, easing microstructural analysis. This experiment employed a Gemini SEM300 field emission SEM-EDS to detect microstructure and elemental dispersal of test specimen materials. Specimens were prepared with a thickness ≤ 5 mm and fingertip-sized cross sections, then dehydrated in a forced-air oven at 80 °C. This prevents water vapor from compromising vacuum integrity, polluting samples, and interfering with image observation. Finally, the test samples undergo gold spraying to enhance their surface conductivity, thereby improving the clarity and stability of subsequent scanning electron microscope images. Figure 4 shows images of the SEM-EDS equipment and on-site operation.



Figure 4. SEM-EDS equipment and specimens.

2.5. Phase Identification

Figure 5 shows images of the XRD equipment and on-site operation. XRD patterns of the CTB specimens were collected using a PANalytical Empyrean diffractometer (PANalytical B.V., Amsterdam, The Netherlands) equipped with a 4 kW Cu $K\alpha$ X-ray source. Phase identification and quantitative analysis of CHSTF were performed according to ASTM C1365–18. The XRD measurements were performed over a 2θ range of $5\text{--}90^\circ$ at a scanning rate of 2°min^{-1} . Prior to analysis, the powdered specimens were oven-dried at 60°C to constant mass.

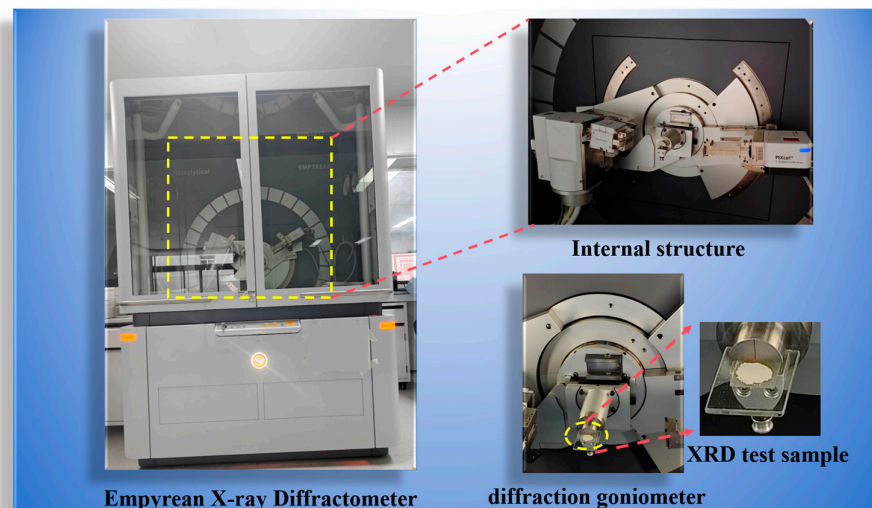


Figure 5. XRD equipment and specimens.

3. Results and Discussion

3.1. Assessing Filled Specimens' Strength Properties

Figure 6 illustrates peak stress histograms under uniaxial compression for different reagents at various dosages. The average peak stress was calculated from each set of three specimens. Differences in fill strength features may be observed under the effects of varying concentrations of Cl^- , SO_4^{2-} , and HCO_3^- . The control specimen prepared without added salts exhibited a compressive strength of 3.04 ± 0.22 MPa. For the Cl^- series, the corresponding strengths at concentrations of 2%, 4%, 6%, 8%, and 10% were 2.48 ± 0.74 , 4.01 ± 0.18 , 3.68 ± 0.06 , 3.55 ± 0.03 , and 1.50 ± 0.12 MPa, respectively. The SO_4^{2-} series yielded strengths of 2.78 ± 0.58 , 3.37 ± 0.21 , 3.42 ± 0.30 , 3.99 ± 0.15 , and 3.63 ± 0.40 MPa, while the HCO_3^- series exhibited strengths of 3.68 ± 0.02 , 1.94 ± 0.23 , 1.87 ± 0.32 , 1.78 ± 0.16 , and 1.59 ± 0.19 MPa, respectively. Overall, the strengths of the Cl^- and SO_4^{2-} systems initially decreased and then increased to peak values at 4% and 8%, respectively, whereas the HCO_3^- system showed a continuous decline after reaching its maximum at 2%.

At a concentration of 2%, both Cl^- and SO_4^{2-} reduced the compressive strength relative to the control, likely because these anions initially interfered with cement hydration by competing with the normal hydration reactions. As their concentrations increased, however, Cl^- promoted the formation of Friedel's salt, whereas SO_4^{2-} facilitated the formation of ettringite and gypsum [50,51]. The resulting hydration products progressively filled internal pores, leading to matrix densification and enhanced strength, with optimum concentrations of 4% for Cl^- and 8% for SO_4^{2-} . In contrast, the initial strength enhancement observed at 2% HCO_3^- is attributed to the precipitation of CaCO_3 , which temporarily densified the pore structure [52].

The sharp strength reduction at 10% Cl^- is likely associated with a threshold effect, whereby excessive Friedel's salt formation induces expansion beyond the tensile capacity of the matrix, leading to microcracking, while severe retardation of cement hydration reduces C-S-H formation. In contrast, the expansive products generated in the SO_4^{2-} system continue to fill pores and partially compensate for matrix damage, thereby delaying the onset of significant strength loss. For the HCO_3^- system, the rapid strength decline after 2% likely reflects the early predominance of cement decalcification and particle coating once CaCO_3 precipitation reaches saturation, after which the rate of deterioration becomes more gradual.

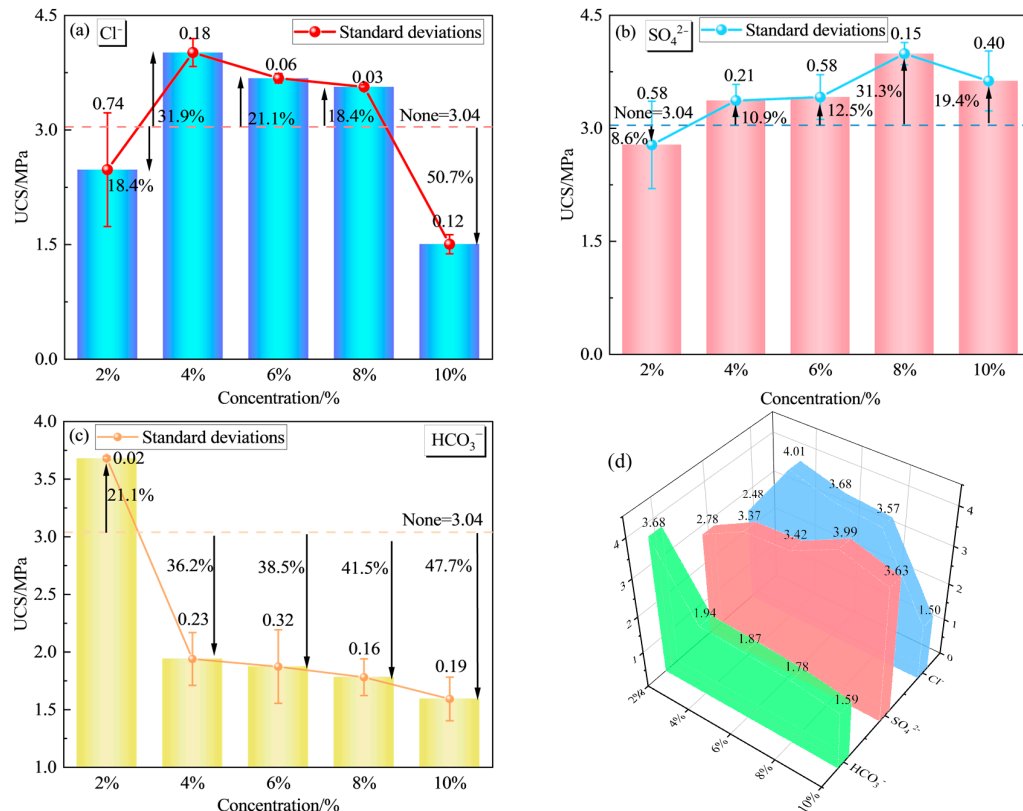


Figure 6. UCS strength of specimens under diverse types and concentration effects: (a) Cl^- ; (b) SO_4^{2-} ; (c) HCO_3^- ; (d) comparison chart.

The elastic modulus was determined from the slope of the initial linear elastic portion of the stress–strain curve and was used to characterize the intrinsic stiffness of the CTB specimens. To minimize the influence of initial pore compaction and seating effects, the secant modulus (E_s) was adopted as a more representative measure of deformation stiffness. In this study, E_s was defined as the secant slope at 50% of the peak stress and calculated according to Equation (1) [53].

$$E_s = \frac{\sigma_{50\%}}{\varepsilon_{50\%}} \quad (1)$$

where E_s denotes secant modulus, $\sigma_{50\%}$ is the agreeing strain at 50% peak stress, and $\varepsilon_{50\%}$ is the agreeing strain at 50% peak stress.

As shown in Figure 7, the evolution of the elastic modulus (E) and secant modulus (E_s) closely follows the trend of uniaxial compressive strength (UCS), indicating a strong correlation between stiffness and strength. The control specimen exhibited E and E_s values of 0.555 ± 0.030 GPa and 0.163 ± 0.024 GPa, respectively. For the Cl^- series, both moduli increased at moderate concentrations but declined sharply at 10%, with E and E_s

decreasing to 0.139 ± 0.014 GPa and 0.088 ± 0.005 GPa, respectively, consistent with the pronounced loss in compressive strength. In the SO_4^{2-} series, E reached its maximum at 6% (0.548 ± 0.010 GPa), whereas E_s peaked at 2% (0.228 ± 0.063 GPa). Notably, the E_s value at 10% (0.185 ± 0.063 GPa) remained higher than that of the control, suggesting that sulfate-induced hydration products continued to enhance deformation resistance despite the slight reduction in strength beyond the optimum concentration. In contrast, HCO_3^- caused a substantial reduction in both stiffness parameters, with E_s remaining consistently below the control at concentrations above 2%, indicating progressive deterioration of matrix rigidity. Overall, these results demonstrate that the evolution of deformation stiffness is closely coupled with strength development, highlighting the synchronous effect of anion-induced hydration and microstructural evolution on the mechanical behavior of CTB.

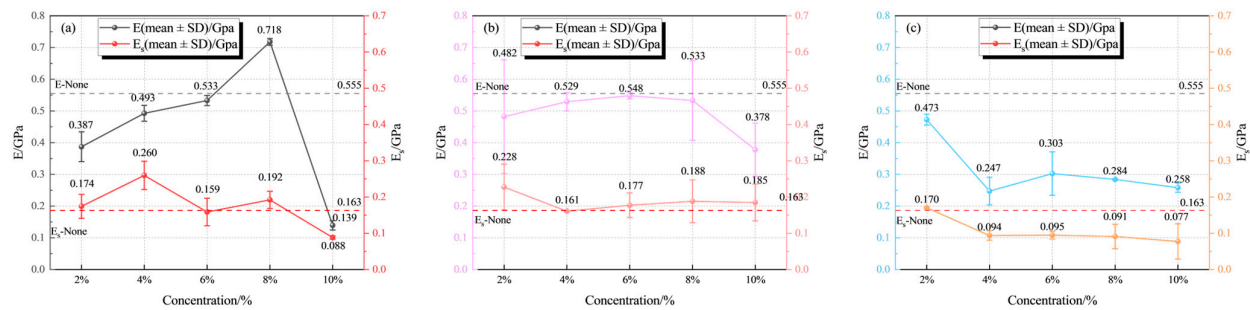
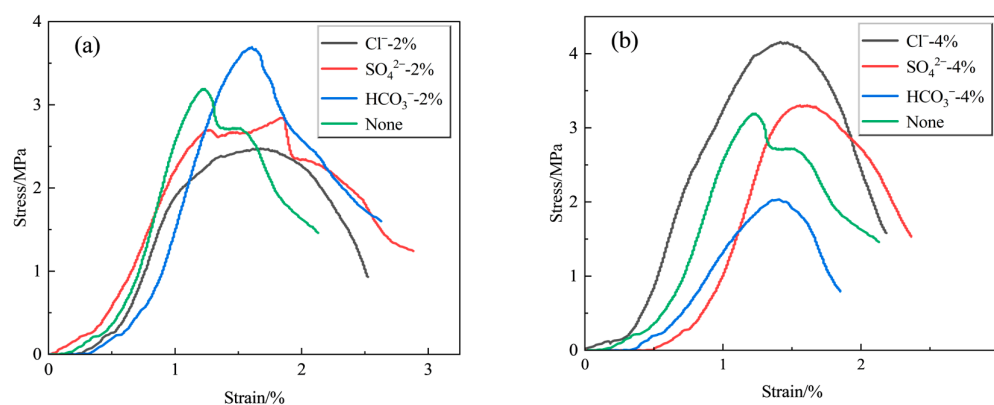


Figure 7. Elastic and secant modulus (E_s) of samples under diverse types and content effects: (a) Cl^- ; (b) SO_4^{2-} ; (c) HCO_3^- .

3.2. Analysis of Stress–Strain Response and Deformation Mechanisms

Figure 8 presents stress–strain behavior of fills under varying ion types and concentrations during UCS experiments. Compression could be divided into four steps: (I) consolidation, where the curve is upwardly concave as microcracks and pores close under pressure; (II) elastic deformation, showing an almost linear response with steady crack development; (III) plastic deformation, characterized by a nonlinear rise toward peak strength, accompanied by nucleation/unstable propagation of new microcracks; (IV) post-peak, marked by a sharp drop in the curve as the main crack rapidly propagates, reducing load-bearing capacity while residual strength persists.



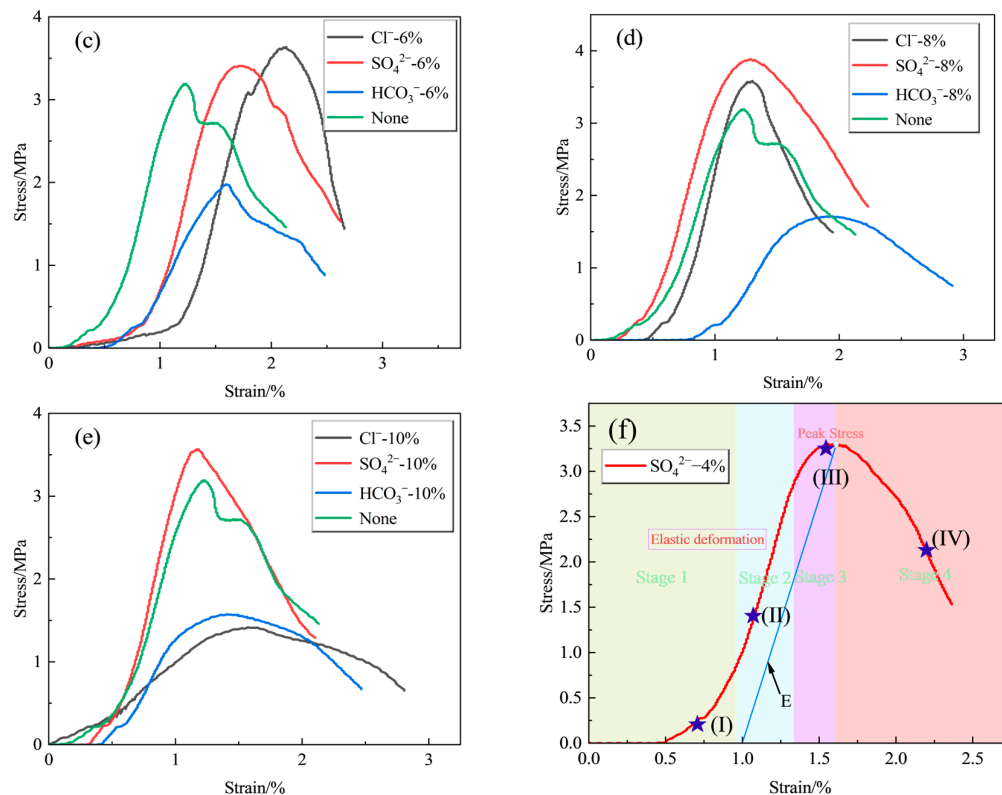


Figure 8. Stress–strain curves: (a) 2%; (b) 4%; (c) 6%; (d) 8%; (e) 10%; (f) deformation failure stage.

Notably, at the optimal ion concentration, peak strength occurs at a later stage, indicating enhanced deformation resistance. This reveals that adding reagent suitably raises the hydration process, effectively improving its internal pore structure. Thus, both its load-bearing capacity and ductility are appropriately enhanced.

At low concentrations ($\leq 4\%$), the stress–strain curve exhibits a relatively broad plateau near the peak point, with a gentle decline slope post-peak. This indicates that the grout maintains residual bearing capacity after reaching peak strength. This phenomenon is attributed to Cl^- accelerating early hydration, thereby promoting pore refinement and matrix densification, which enhances the toughness and energy dissipation capacity of the grout [54]. As the Cl^- concentration increases, the curve morphology undergoes changes: the peak point shifts forward, the post-peak curve exhibits a steep slope, and a trend of abrupt stress decline appears after the peak. This reflects that, at high Cl^- concentrations, the original C_3A forms expansive Friedel's salts. After filling pores and cracks, these salts continue to expand and increase in volume, eroding the internal cementitious structure and causing the filling material to disintegrate. However, at a 10% concentration, the specimen exhibits low strength but a relatively gradual post-peak stress decline. This indicates that the hydration products partially fill the pores at this concentration, enhancing toughness.

SO_4^{2-} exhibits typical expansion-erosion features. At low concentrations, elastic stage stiffness rises slightly, with a relatively gentle decline after the peak, corresponding to filling and compaction of pores by early hydration products like calcium vanadate. At an 8% concentration, the specimen exhibits the highest peak strength and a relatively smooth post-peak response, suggesting that the expansive hydration products primarily promote pore filling and matrix densification at this stage [55]. At a 10% concentration, a typical brittle failure pattern emerges, with a quick failure after the peak. This suggests that products like calcium aluminate hydrate generated at this stage are insufficient to counteract

the expansion stress exceeding the loss from their fill impact, causing a cut in strength. The curve exhibits a trend of falling peak strength with increasing concentration and a gradually steeper slope in the post-peak segment.

When HCO_3^- concentration is excessively high, it reacts with free calcium ions and calcium ions within C-S-H to create calcium carbonate. Excessive CaCO_3 precipitation hinders cement hydration by coating cement particles, thereby reducing the formation and binding capacity of hydration products [56]. Simultaneously, it reduces the pore solution pH. As pH decreases, C-S-H, $\text{Ca}(\text{OH})_2$, and AFt decompose. This manifests as a trend in the curve where peak strength decreases with growing concentration, and the post-peak section gradually steepens, with strength gradually diminishing.

3.3. Energy Dissipation Analysis

During uniaxial compression, the external work supplied by the testing machine is mainly stored as elastic strain energy within the specimen, although the rest is debauched by irreversible damage processes, including microcrack initiation, propagation, and closure [57,58]. Assuming adiabatic loading, total input U , elastic strain U_e , and dissipated U_d energies can be quantified using the formulations given in [59–61]. Using the formula to calculate each energy value, Figure 9 shows the energy dissipation curves for different reagents at various loading rates under uniaxial compression. Energy dissipation ceases at 50% stress within the post-peak stage.

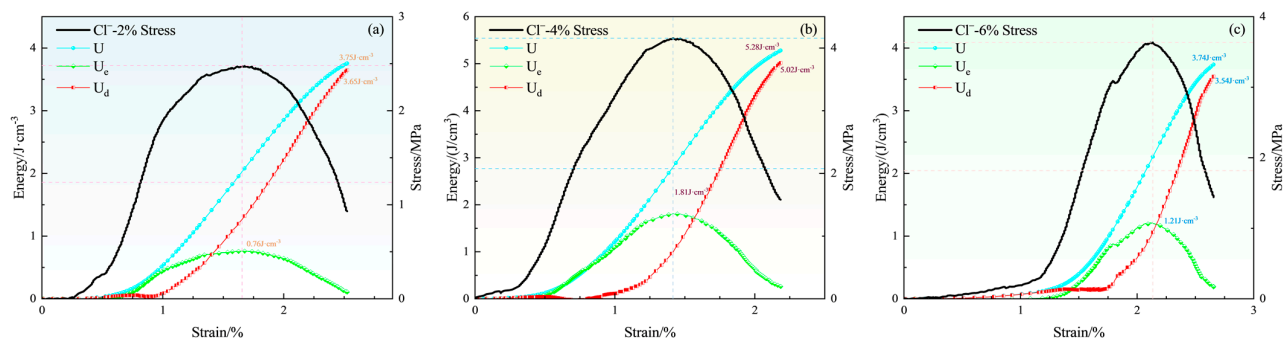
$$U = U_e + U_d \quad (2)$$

$$U = \int \sigma dx \quad (3)$$

$$U_e = \frac{\sigma^2}{2E} \quad (4)$$

where U denotes total energy, U_e denotes elastic strain energy, U_d denotes dissipated energy, σ terms stress, ϵ terms strain, and E terms Young's modulus.

One can see that U exhibits a non-stop growing trend by mounting strain. U_e follows a similar trend as the stress–strain curve. During the test's initial stage, U_e in the specimen continues to accumulate. As the load persists, samples fail, causing the elastic strain energy to be suddenly released. This results in a trend where elastic strain energy rises gradually before abruptly decreasing. The dissipated energy exhibits a trend of slow initial growth followed by a sharp increase after failure occurs. Based on the energy variation trend, the specimen's energy curve demonstrates distinct patterns across the four stress–strain stages.



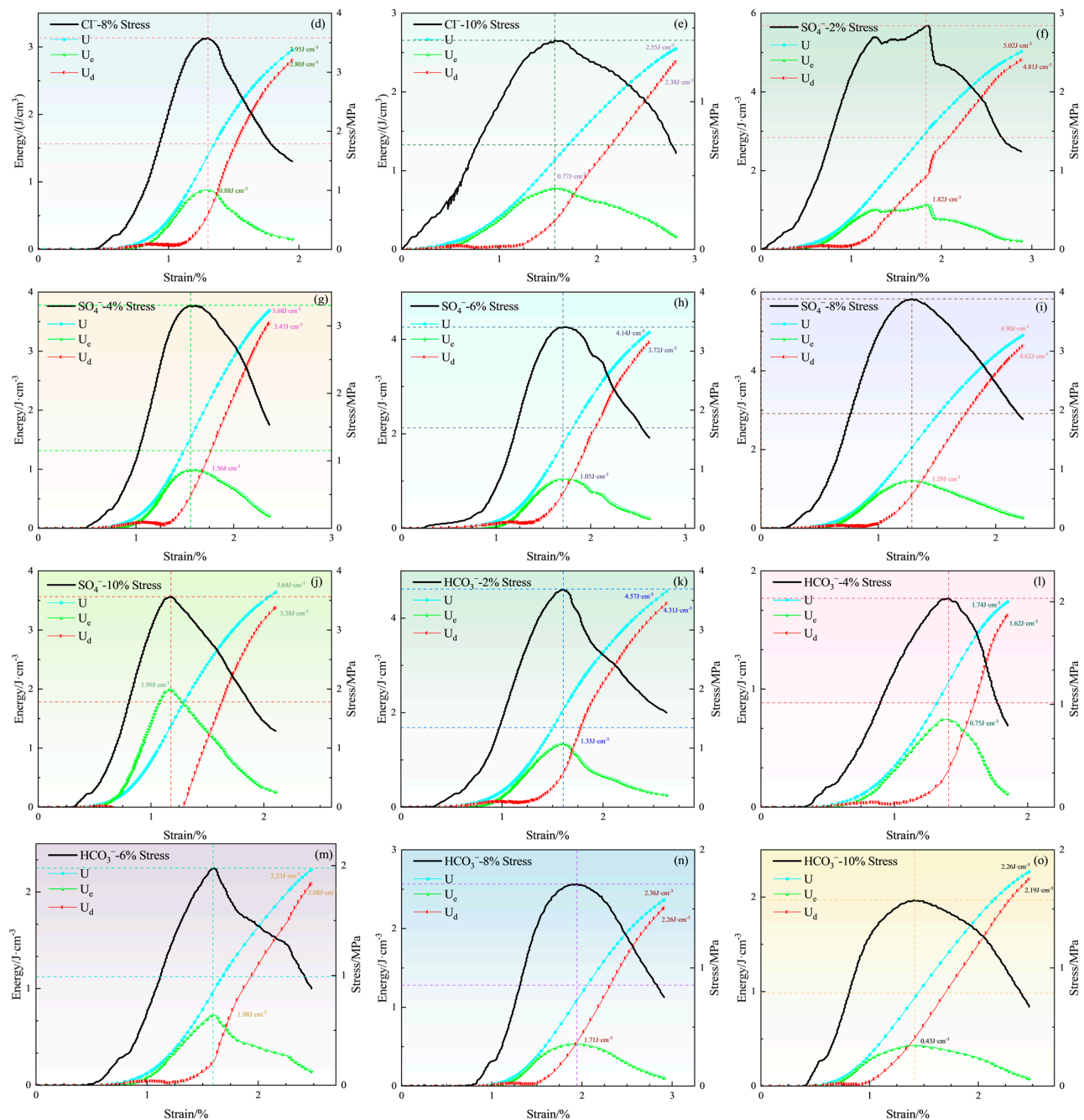


Figure 9. Energy dissipation curve of UCS test under different types and concentrations. (a) Cl^- -2%; (b) Cl^- -4%; (c) Cl^- -6%; (d) Cl^- -8%; (e) Cl^- -10%; (f) SO_4^{2-} -2%; (g) SO_4^{2-} -4%; (h) SO_4^{2-} -6%; (i) SO_4^{2-} -8%; (j) SO_4^{2-} -10%; (k) HCO_3^- -2%; (l) HCO_3^- -4%; (m) HCO_3^- -6%; (n) HCO_3^- -8% (o) HCO_3^- -10%.

The U values of Cl^- -containing specimens at different concentration gradients were 3.57, 5.28, 3.74, 2.95, and 2.55 J/cm^3 , respectively. It can be observed that the energy of the Cl^- -4% specimen reached its maximum simultaneously with its peak intensity. As the concentration continued to increase, its energy decreased to 3.74 J/cm^3 , indicating that chloride ions began to reduce the internal structural stability at this point. At a concentration of 10%, the specimen's strength and toughness deteriorated comprehensively. The U values of the SO_4^{2-} -containing specimens at different concentration gradients were 5.02, 3.68, 4.14, 4.90, and 3.64 J/cm^3 . Although specimen strength increases—attributable to enhanced Aft formation and improved density—this leads to reduced U values and increased

brittleness. Upon reaching the optimal concentration, Aft induces an increase in internal microcracks, raising the porosity and causing a reduction in the energy absorption capacity. The U -values of HCO_3^- containing specimens under different concentration gradients were 4.57, 1.74, 2.23, 2.36, and 2.26 J/cm^3 , respectively. One can witness that energy decreases with increasing concentration. This correlates with the reduction in internal pH caused by high HCO_3^- concentrations, causing the C-S-H gel's decalcification and decomposition. This lowers internal bond strength, reduces toughness, and facilitates the instability and propagation of microcracks.

3.4. Characterization of CTB Fracture Evolution

Figure 10 shows the binarization of surface cracks on specimens under different types and concentrations. According to the processing results diagram, the blank group primarily exhibited circumferential tensile cracks, accompanied by a small number of associated microcracks. As the chloride ion concentration rises, the failure behavior of Cl^- -2% specimens changes from two longitudinal cracks to a through-shear crack compared to Cl^- -2% specimens. This indicates that high chloride ion concentrations further destabilize the hydration products. Excessive formation of expansive products raises internal pore pressure and reduces cementing properties, leading to more pronounced shear-type macroscopic failure [62]. It is evident that compared to SO_4^{2-} -2% specimens, the SO_4^{2-} -10% specimens exhibited localized peeling rather than large-scale flaking after failure. This behavior corresponds to their uniaxial compressive strength, which showed a rise in comparison with the control group. This suggests that an increasing sulfate ion concentration hastens the rate of hydration and enhances hydration crops' creation [63].

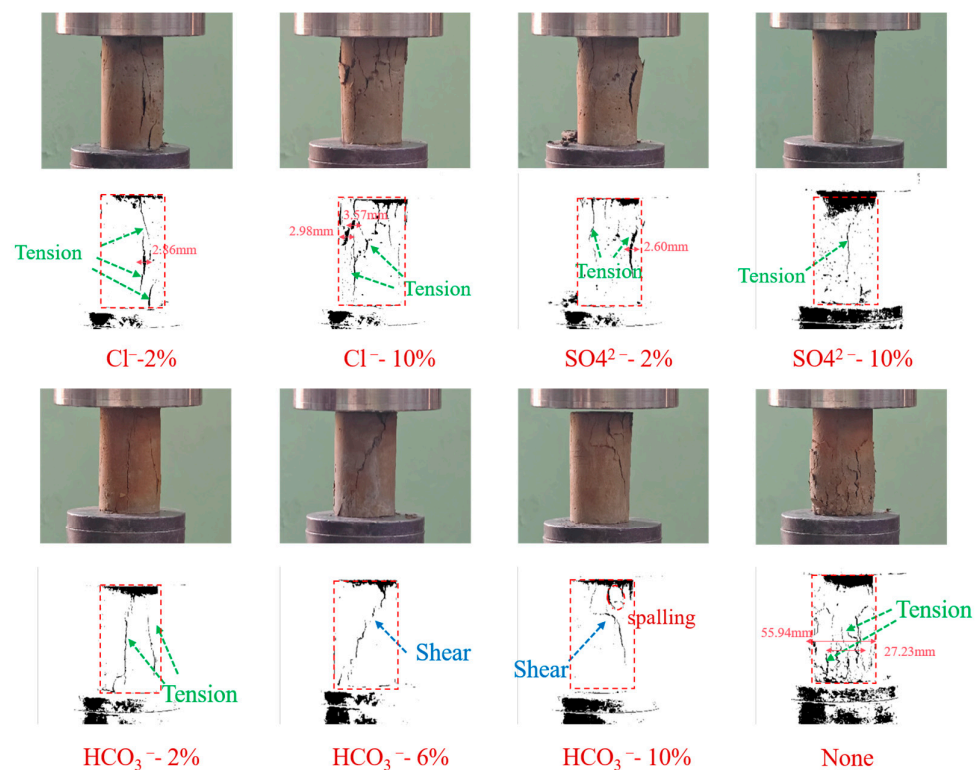


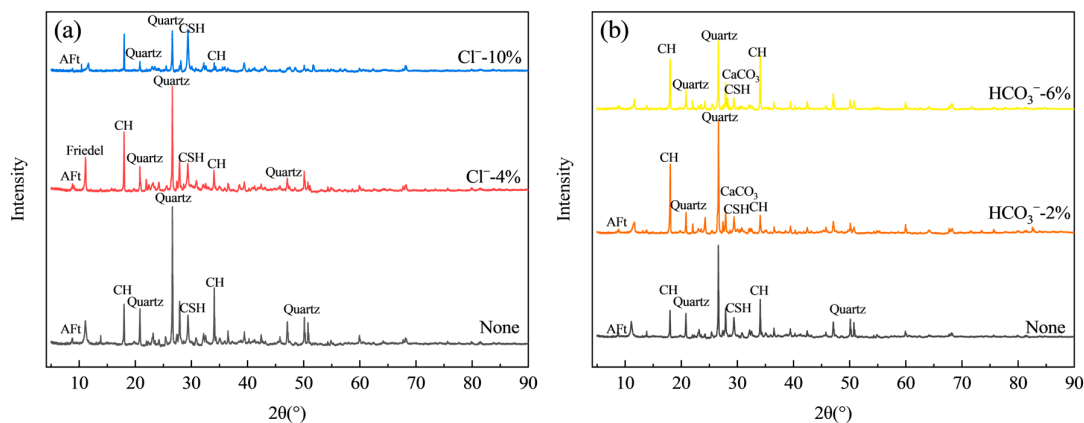
Figure 10. Failure modes of uniaxial compressive test under different types and concentrations.

The specimens with HCO_3^- -2% primarily exhibited two parallel tensile cracks, indicating that the stress transfer during specimen failure was predominantly in the vertical direction. The HCO_3^- -6% specimen primarily exhibited a single shear crack. The HCO_3^- -

2% specimen, with its lower concentration, featured fine calcium carbonate particles filling the pores and a dense matrix, resulting in higher tensile strength. The cracks did not penetrate fully, primarily manifesting as two tensile cracks. The HCO_3^- -6% specimens primarily exhibited a shear crack. This was largely owing to excessive consumption of C-S-H by HCO_3^- , causing reduced bonding strength and consequently diminished shear resistance. This caused the crack to transition from tensile to shear failure, manifesting as localized flaking [64]. The specimens with 10% HCO_3^- exhibited severely impeded hydration due to excessively high HCO_3^- concentration, resulting in extremely poor internal cohesion. Shear cracks propagated continuously through specimens, accompanied by localized lifting/spalling of small fragments, exhibiting combined shear-splitting failure.

3.5. Evolution of Crystalline Phases from XRD Analysis

Figure 11 illustrates the XRD patterns of 7-day hydration crops under diverse ion types and concentrations. A peak appears near $2\theta = 11^\circ$ at Cl^- -4%, indicating the formation of a characteristic Friedel salt hydrate product after chlorine salt addition. At this 4% reagent concentration, the filler's strength features are boosted [65]. Moreover, a prominent peak at $2\theta = 29^\circ$ under high concentrations indicates that chloride ions can accelerate hydration in the short term, generating more gel. However, Friedel's salts and calcium aluminate continue to expand and increase in volume, thereby reducing the strength of the backfill. Peaks appear near both $2\theta = 22^\circ$ and 26° , precisely corresponding to the chemical composition of SiO_2 in the tailings. At $2\theta = 18^\circ$ and 34° , standard peaks and secondary peaks appear, respectively, corresponding to the product of Portland stone Ca(OH)_2 . SO_4^{2-} and HCO_3^- respond by Ca(OH)_2 to create CaSO_4 and CaCO_3 , respectively. Consequently, the characteristic peak at $2\theta = 18^\circ$ for the hydrated product Ca(OH)_2 is reduced. This promotes hydration reactions, generating more AFt and C-S-H [66]. At high ionic concentrations, the peak around $2\theta = 29^\circ$ becomes more pronounced, precisely corresponding to increased C-S-H content. This cuts internal porosity and boosts mechanical strength. HCO_3^- content of 6% exhibits reduced peak intensity at $2\theta = 18^\circ$ and $2\theta = 34^\circ$. This is clarified by undue existing HCO_3^- ions, causing decalcification of Ca(OH)_2 from the C-S-H phase, resulting in diminished strength [67].



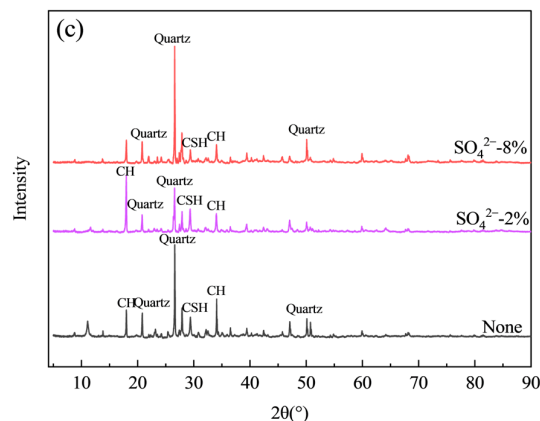
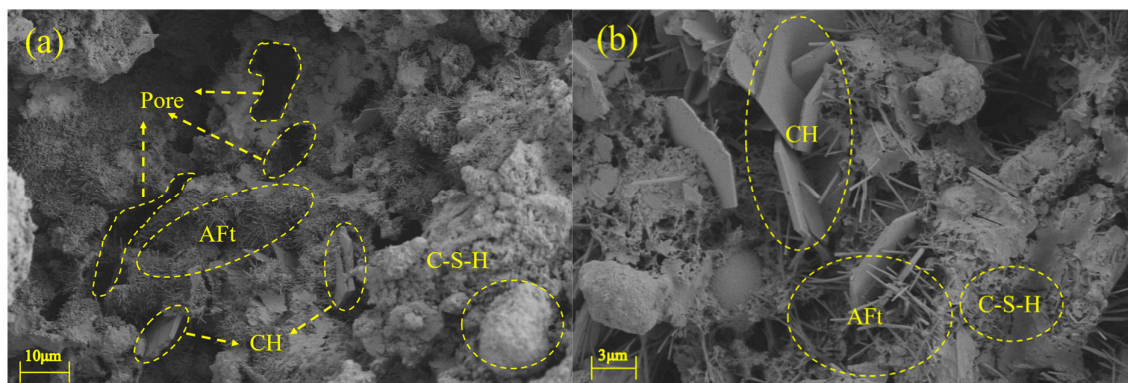


Figure 11. XRD results of CTB under different types and concentrations. (a) Cl^- -4% and Cl^- -6%; (b) HCO_3^- -2% and HCO_3^- -6%; (c) SO_4^{2-} -2% and SO_4^{2-} -8%.

3.6. SEM Analysis of Microstructural Development and Damage

SEM analysis was executed on specimens subjected to uniaxial compression without added reagents and with added 2%, 4%, and 10% NaCl, 6% and 8% Na_2SO_4 , and 2% and 6% NaHCO_3 (Figure 12). For the blank group without added reagents, conventional hydration crops (i.e., C-S-H and CH) are visible, exhibiting a more porous structure. This contrasts sharply with the hydration products formed after subsequent reagent addition. The addition of bicarbonate ions to the sample produces characteristic spherical goethite crystals that fill the internal pores well, enhancing density while accelerating the hydration reaction. This promotes the formation of AFt and CH, resulting in a denser hydration matrix and consequently enhanced mechanical performance. The addition of sulfate ions produces abundant needle-like AFt crystals, which interlock to densify the microstructure and improve early-age strength [68,69]. Upon magnified observation of the internal structure, needle-like C-S-H crystals are visible interwoven within the C-S-H matrix. These crystals aptly fill the porous gel structure while exhibiting excellent interfacial bonding. Mechanical properties are also moderately enhanced. However, as sulfate ion concentration increases, excess calcium aluminate hydrate and gypsum formed expand and damage the specimens. This also initiates C-S-H's decalcification, resulting in weakened skeletal connectivity. Specimens containing chloride ions react with CH to accelerate the hydration of C_3A , generating more AFt. Simultaneously, they accelerate the hydration rate of C_3S , producing more C-S-H gel. This lessens internal porosity and tightens the skeletal connections, effectively enhancing mechanical properties [35]. However, when chloride ion concentrations become excessively high, the characteristic product Friedel's salt continues to expand after filling internal pores and cracks, thereby reducing its mechanical properties.



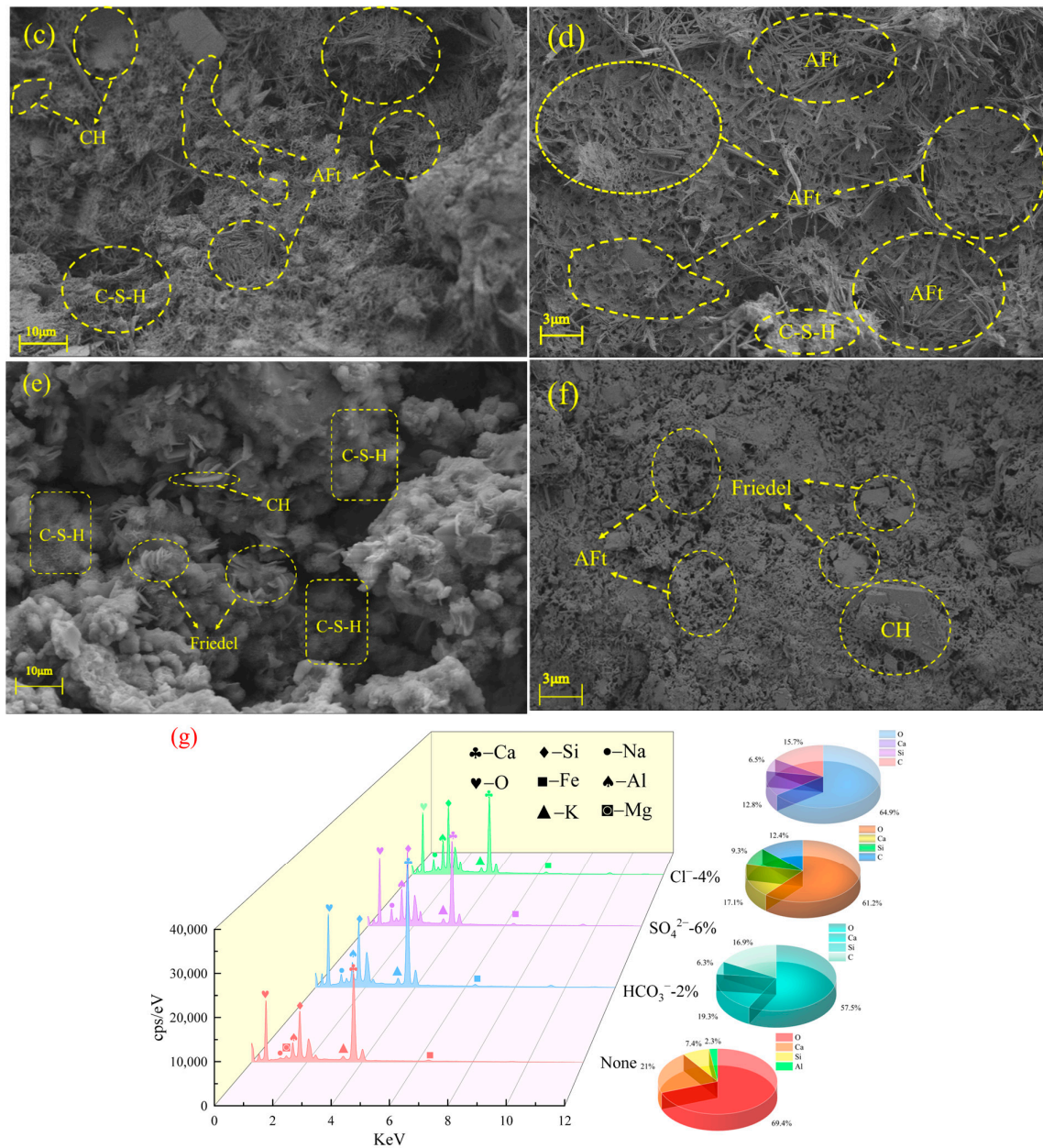
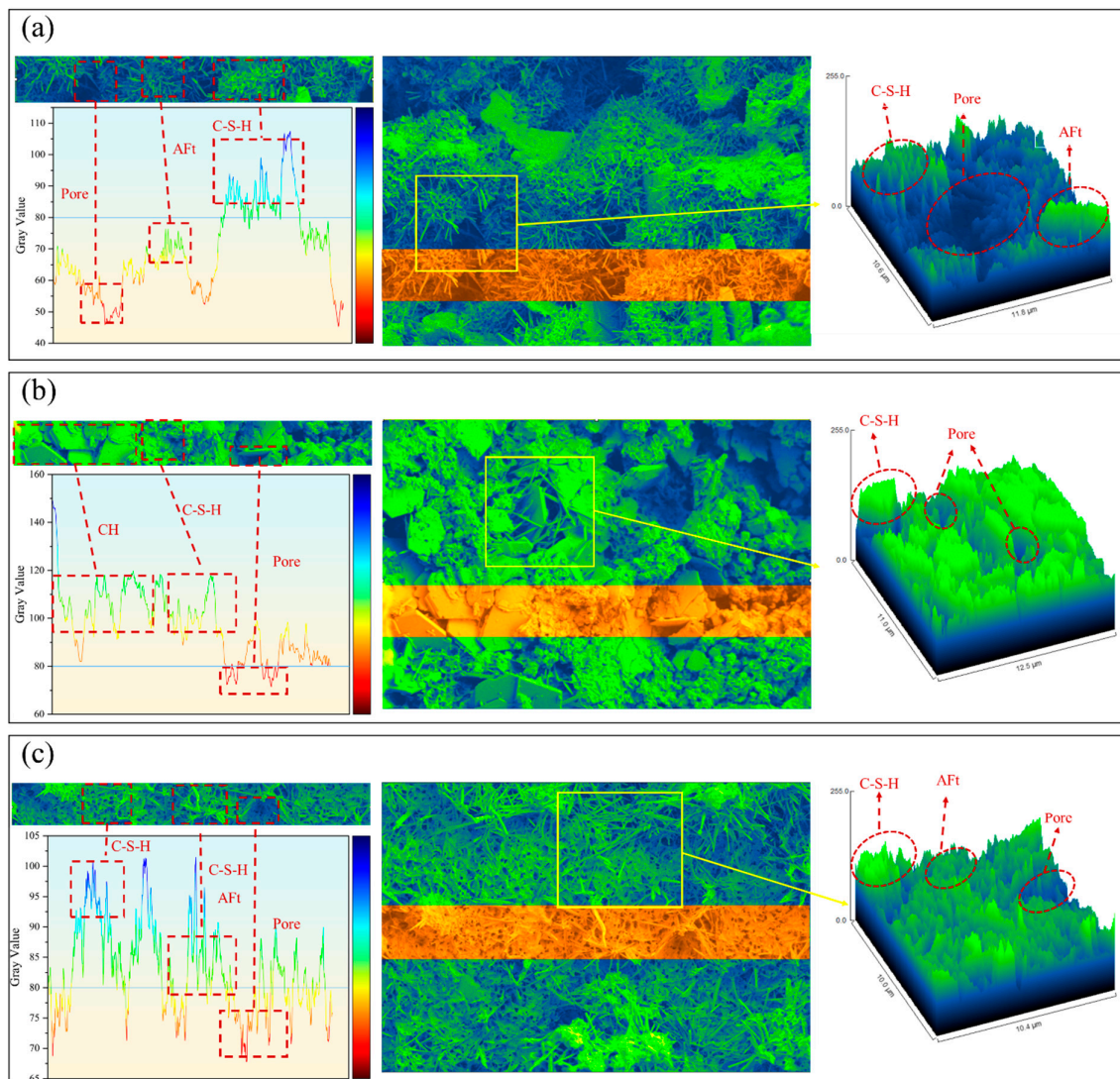


Figure 12. SEM results of CTB under different types and concentrations: (a) none; (b) HCO_3^- -2%; (c) SO_4^{2-} -6%; (d) SO_4^{2-} -8%; (e) Cl^- -4%; (f) Cl^- -10%; (g) EDS results.

The main EDS analysis revealed that the elements corresponding to the peaks in each group matched the material XRD results. The primary elements were O, C, Na, and Si. In the blank group, O and Ca primarily originated from $\text{Ca}(\text{OH})_2$ and C-S-H. Si and Al originated from C-S-H and unhydrated silicate and aluminite minerals. Adding 2% HCO_3^- triggers a carbonation reaction, producing calcium carbonate and introducing an amount of carbon. The formation of gypsum and calcium aluminate in the SO_4^{2-} -6% sample consumed an amount of Ca^{2+} , leading to a sharp decrease in the Ca content measured by EDS. Due to this substantial Ca consumption, the relative proportion of Si in remaining C-S-H appears higher. Cl^- bonds to Al phases (C_3A) to create chloraluminates, with some Ca being immobilized in Friedel salts, resulting in reduced Ca content.

The SEM grayscale analysis provides a qualitative indication of relative microstructural densification rather than a quantitative measure of porosity. Quantitative porosity

characterization (e.g., by MIP) was beyond the scope of this study. Figure 13 displays a high-magnification SEM image with pseudo-color processing applied. High gray-scale regions signify the buildup of dense hydration phases accompanied by irregular surface topography [70]. In Figure 12a, the primary hydration products in the blank group are flocculent hydration gel and AFt. The surface gray values range from 43 to 107, with most of the gray value curve falling below 80. This indicates distinct regions where gray values decrease due to pore structure. Figure 12b–d correspond to gray value ranges of HCO_3^- -2%, SO_4^{2-} -8%, and Cl^- -4% specimens, respectively, which are 73–149, 68–100, and 63–103. The gray value curves are predominantly above 80. Higher grayscale values qualitatively reflect a denser hydrated microstructure in the selected SEM fields. At the optimum ion concentration, the SEM images reveal a more homogeneous and compact gel matrix, indicating enhanced microstructural densification.



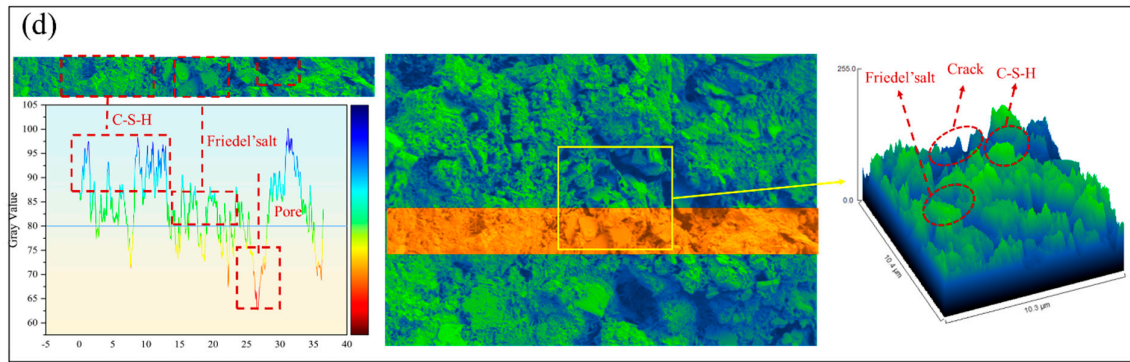


Figure 13. Inner texture and gray value of CTBs: (a) none; (b) HCO_3^- -2%; (c) SO_4^{2-} -8%; (d) Cl^- -4%.

4. Conclusions

This study utilized tailings and cement as primary raw materials, preparing CTB specimens by mixing them with a solution covering a gradient concentration of three reagents— NaCl , Na_2SO_4 , and NaHCO_3 —to simulate different ionic environments. It examines the uniaxial compressive strength, stress–strain characteristics, and energy dissipation properties of specimens under varying concentrations and types of ions at the macro level. The phase growth and microstructure features of fills under different conditions are clarified. Key findings are summarized below:

- (1) The mechanical performance of CTB is strongly influenced by both the type and concentration of dissolved salts in the mixing water during the 7-day curing period. Overall, the incorporation of chloride-, sulfate-, and bicarbonate-based sodium salts at their optimum concentrations increased the compressive strength of CTB by approximately 30% relative to the control specimen. However, further increases in salt concentration reduced the strength, with the most pronounced deterioration observed in bicarbonate-containing mixtures.
- (2) The energy evolution of CTB closely corresponds to its stress–strain response. Total and dissipated energies increase progressively with strain, whereas elastic strain energy accumulates during loading and is rapidly released upon failure. At the optimum ion concentrations, the energy dissipation capacity was significantly enhanced, with the total input energy reaching 5.28 J/cm^3 for Cl^- (4%), 4.90 J/cm^3 for SO_4^{2-} (8%), and 4.57 J/cm^3 for HCO_3^- (2%), demonstrating improved toughness and ductility relative to the control specimen.
- (3) The fracture behavior was closely correlated with the mechanical strength of CTB. At higher strength levels, failure was dominated by tensile splitting. However, excessive concentrations of Cl^- and HCO_3^- shifted the failure mode to a single through-going shear crack accompanied by localized spalling, resulting in a marked reduction in strength. In contrast, SO_4^{2-} specimens predominantly retained tensile failure characteristics even at high concentrations, without exhibiting severe brittle strength degradation.
- (4) XRD and SEM–EDS analyses elucidate the microstructural mechanisms governing the single-anion systems investigated in this study. Qualitative observations indicate that appropriate concentrations of Cl^- , SO_4^{2-} , and low-level HCO_3^- promote the formation of hydration products that produce a denser and more homogeneous microstructure. In contrast, excessive anion concentrations induce expansive reactions or cement decalcification, resulting in microstructural deterioration and a corresponding decline in mechanical performance.

This study is limited to an early curing age of 7 days. As no tests were conducted at 28, 56, or 90 days, the optimum ion concentrations and the proposed mechanisms are applicable only to the early-age mechanical behavior of CTB.

Within the single-anion systems investigated, excessive Cl^- and HCO_3^- concentrations promoted a transition to catastrophic shear failure, highlighting the need to strictly control their levels in CTB mixing water. In contrast, moderate SO_4^{2-} concentrations enhanced strength without inducing brittle failure. These findings establish a mechanistic baseline for future studies on multi-ion mine water, which are required to accurately predict and optimize the long-term in situ performance of CTB.

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Data Availability Statement: No new data were created or analyzed in this study.

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