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Experimental investigation on the performance degradation of grouting materials in karst erosion environment

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The fundamental cause of leakage in grouting curtains of dams in karst areas lies in the localized damage induced by performance degradation of the curtain under seepage-induced erosion. This work investigated the degradation mechanisms of grouting curtains exposed to karst water erosion by analyzing the mechanical and microstructural evolution of cement-grouted stone (CGS) and cement-clay-grouted stone (CCGS). The results indicate that both materials experience progressive deterioration in mechanical properties, with CCGS demonstrating significantly higher vulnerability. After 120 days, the compressive strength of CGS decreased from 32.89 MPa to 20.03 MPa, while the strength of CCGS declined sharply from 3.89 MPa to 2.03 MPa. Porosity increased from 26.06% to 33.91% for CGS and from 58.04% to 77.01% for CCGS. Microstructural analysis revealed that karst water induced chemical erosion and structural damage in both materials, with CCGS exhibiting accelerated degradation due to weaker cementitious bonding and higher initial porosity, which facilitated ion penetration and reaction-induced damage. The findings highlight the inferior durability of cement-clay composites under karst water conditions and provide critical insights for optimizing grouting materials in karst-prone environments.

KEYWORDS

karst, grouting curtain, erosion effect, performance degradation, grouted stone

1 Introduction

Grout curtain grouting is the preferred construction method for anti-seepage reinforcement of dams in karst regions. However, the karst stratum contains interconnected fissures and conduits with mineral-rich groundwater, where the synergistic effects of hydrostatic pressure, chemical interactions, and geostress can readily induce deterioration and structural damage to the grouting curtain (Liu, 2004; Yu et al., 2020). Extensive engineering projects have demonstrated that the cause of seepage incidents in dam grouting curtains within karst areas lies in the performance degradation of curtain structures under seepage-induced erosion, ultimately leading to localized failures, as evidenced by the Tangab Dam (Mozafari et al., 2021), Logan Martin Dam (Bruce et al., 2017), and Teton Dam (Verma et al., 2023).

Currently, scholars primarily characterize the performance degradation of grouting curtains by investigating changes in the physical-mechanical properties of grouted stones under karst water erosion (Ahmad et al., 2019; Wei et al., 2025), a method whose feasibility has been validated. For instance, Liu (2019) conducted accelerated dissolution tests to obtain the compressive strength, cohesion, internal friction angle, permeability coefficient, and microstructural characteristics of grouted samples at different curing ages. Recent work also emphasizes the temperature field evolution in backfill materials, which could correlate with chemical and mechanical degradation pathways in similar subsurface environments (Ahmad et al., 2021). Feng (2015) compared the soft-water erosion resistance of cement-clay grouts with varying mix ratios through orthogonal experiments, analyzing the degradation patterns of cement-clay reinforcements under different erosion media and durations using strength and mass loss as performance indicators. Sha and Fan (2021) investigated the early impermeability, flexural strength, unconfined compressive strength, corrosion resistance coefficient, volume/mass variations, fracture surface characteristics, corrosion minerals, microstructure, and pore size distribution of a novel high-efficiency micro-cement grouting material in corrosive environments. Tu (2012) evaluated the durability of cement-based grouting materials in seawater using fuzzy analytic hierarchy analysis based on seawater erosion resistance tests. Wang et al. (2021) and Wang et al. (2020), addressed grouting design challenges in sand layers under seawater erosion by conducting accelerated degradation tests, establishing quantitative relationships between seawater exposure time and grouted reinforcement strength, and proposing a constitutive model for degradation damage, providing theoretical guidance for sand-layer grouting in marine environments. Fu et al. (2013) enriched durability prediction frameworks by comparing erosion rates of cement grouting curtains under low-alkalinity soft water at varying permeation pressures.

However, the initial performance of grouted stones is closely tied to grouting environments of karst dams, construction parameters, and material properties-factors often overlooked in existing studies. This oversight leads to significant discrepancies between the performance of laboratory-tested grouted stones and the behavior of real-world karst dam grouting curtains, limiting the practical applicability of experimental findings. Thus, this work simulated the erosion environment of karst dam grouting curtains by preparing high-concentration karst water curing solutions and controlling curing temperatures based on accelerated erosion principles. Specimens cured for varying durations undergo tests for compressive strength, porosity, mass loss, and microstructural morphology to elucidate the performance degradation mechanisms of karst dam grouting curtains under aggressive environmental conditions. Modeling approaches have also been applied to understand cemented geomaterial behavior under similar erosive and structural loading conditions (Rizvi et al., 2020a).

2 Methods

2.1 Raw materials and preparation

The experiment used pure cement grout and cement-clay grout to create grouted stone samples, with mix proportions corresponding to standard practices for grouting curtains in karst areas. The cement utilized was again 42.5R Ordinary Portland Cement, adhering to the national standard of normal Portland cement in China. The clay component consisted of specialized calcium-based clay from Lingshou County, Hebei Province, China. The water-cement ratio for the pure cement slurry was 1:2, while the mixing ratio for the cement-clay slurry was 2:1, with the clay content making up 50% of the cement weight. The grouting process parameters, such as pressure and duration, play a critical role in ensuring uniform penetration and minimizing head losses during injection, as highlighted in prior fluid dynamics studies (Haroon et al., 2017). During the preparation process of grouting stone bodies, a grouting pressure of 1 MPa was applied for a duration of 6 s. The samples were cured under standard conditions of 20°C ± 1°C and ≥95% humidity. Figures 1–3 illustrate the test preparation process, test equipment and grout stone samples.

2.2 Design of accelerated degradation test

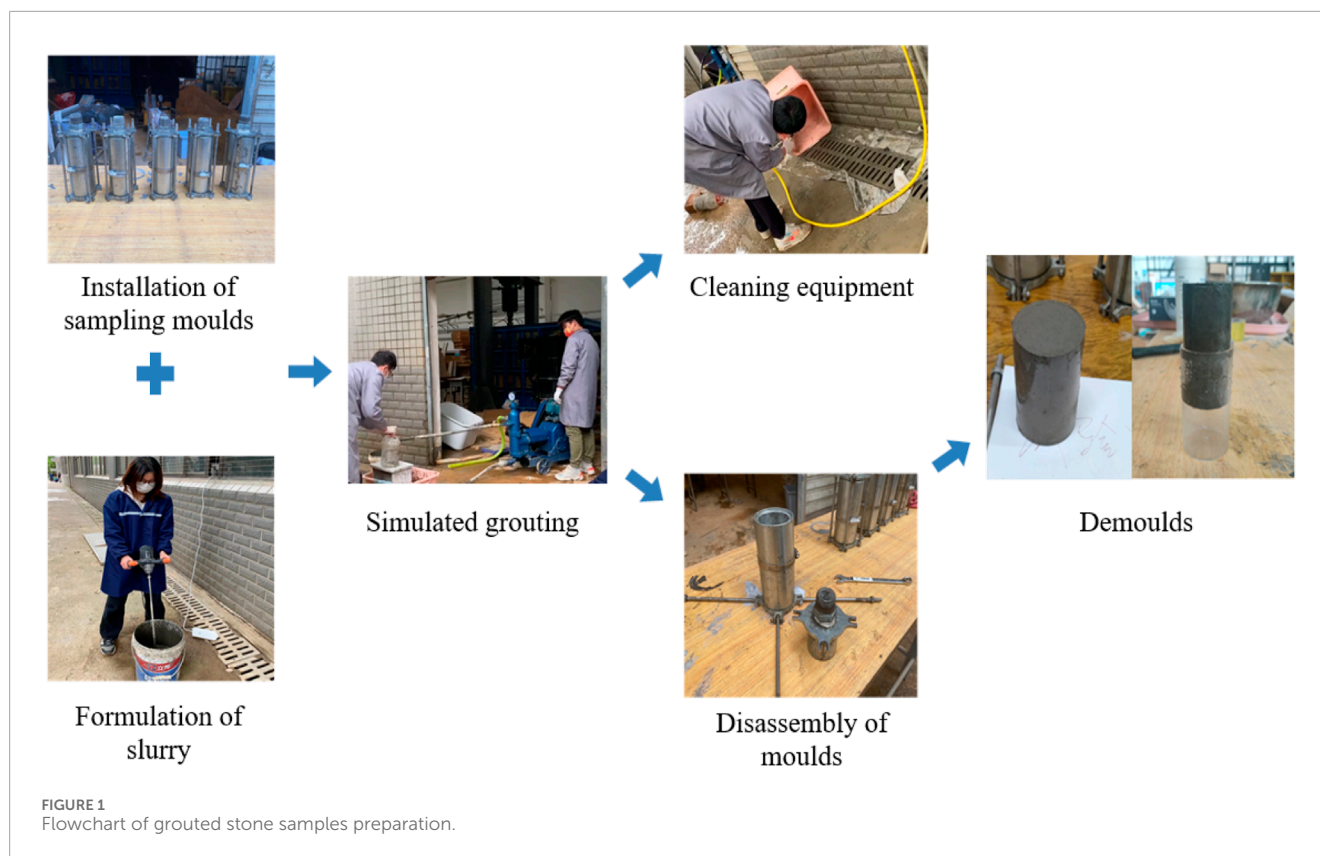
The critical challenge in conducting laboratory accelerated degradation tests lies in constructing an accelerated erosion environment that effectively replicates the long-term service conditions of grout curtains. In this work, the degradation process of grouted specimens was accelerated by controlling the concentrations of aggressive ions in simulated karst groundwater and adjusting the curing temperature. The transport mechanisms governing the ingress of aggressive ions into grouted matrices typically include adsorption, diffusion, pressure-driven permeation, and dispersion. Among these, the diffusion of aggressive ions is generally considered to be the most important migration mechanism (Yu and Sun, 2006). When neglecting the binding capacity of aggressive ions within grouted matrices and the influence of time-dependent structural defects on diffusion coefficients, the theoretical model for ion diffusion can be derived from Fick's Second Law (Yu and Sun, 2006; Wang, 2016), as shown in Equation 1 and Equation 2.

$$c = c_0 + (c_s - c_0) \left(1 - \operatorname{erf} \frac{x}{2\sqrt{Dt}} \right) \quad (1)$$

$$\operatorname{erf} u = \frac{2}{\pi} \int_0^u e^{-t^2} dt \quad (2)$$

where c_0 and c_s are the initial erosive ion concentration in the grouted stone and the erosive ion concentration on the exposed surface, respectively. And erf is the error function.

According to the test design, it can be considered that $c_0 = 0$, then Equation 1 can be simplified to Equation 3:



$$c = c_s \left(1 - \operatorname{erf} \frac{x}{2\sqrt{Dt}} \right) \quad (3)$$

Therefore, the diffusion of aggressive ions in the experiment exhibits direct proportionality to the surface concentration c_s . When the erosive ion concentration at the exposed surface of grouted matrices increases by a factor of 20, the corresponding acceleration factor s_1 for the test duration also increases by 20 times.

The fundamental mechanism of aggressive ion diffusion in grouted matrices involves random thermal motion of ions through the pore solution within the matrix. The diffusion coefficient of aggressive ions demonstrates a positive temperature dependence (Lindvall, 2007). As described by the Arrhenius equation (Zuo, 2021), the influence of ambient temperature on the diffusion of aggressive ions within grouted matrices is quantified by Equation 4:

$$D_t(T) = D_0 e^{\frac{E}{R} \left(\frac{1}{T_0} - \frac{1}{T} \right)} \quad (4)$$

where: D_0 is the diffusion coefficient of aggressive ions at temperature T_0 , m^2/s ; D_T is the diffusion coefficient of aggressive ions at temperature T , m^2/s ; T_1 is the reference temperature, generally 293 K; E/R is the activation energy, which is taken as 14,242 in reference (Wang, 2019).

According to literature (Jiang et al., 2014; Pan et al., 2023), the annual average water temperature of rivers in Changsha area is about 18°C (290.9 K), and constant temperature 30°C (303 K) was used in

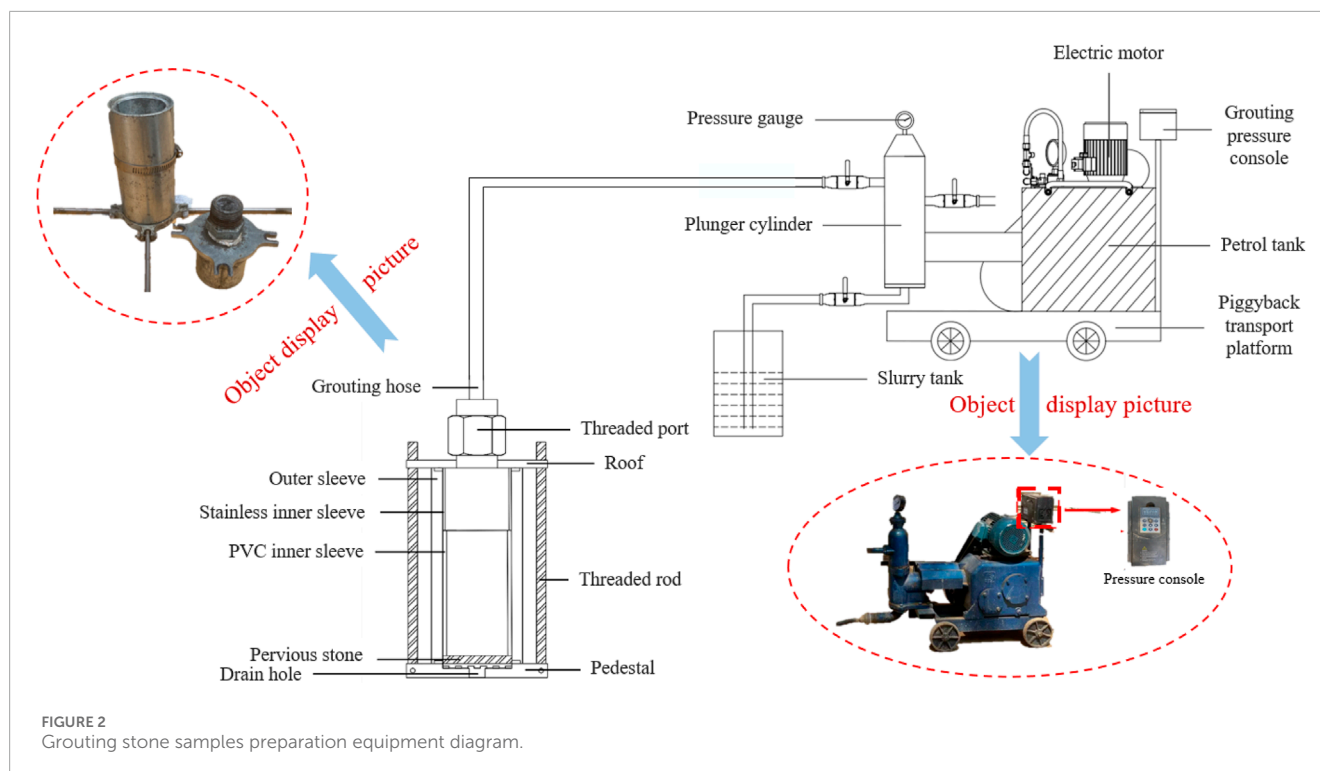
this experiment to maintain the grouted stone test. The acceleration coefficient s_2 is calculated in Equation 5.

$$S_2 = \frac{D_T(303)}{D_T(290.9)} = \frac{D_0 e^{14242 \left(\frac{1}{293} - \frac{1}{303} \right)}}{D_0 e^{14242 \left(\frac{1}{293} - \frac{1}{291} \right)}} = 6.95 \quad (5)$$

Therefore, the total acceleration coefficient S of this degradation test is equal to the product of external erosive ion concentration and temperature acceleration coefficient, that is, $S = 138.94$.

Based on the pre-determined 20 times accelerated erosion factor, the karst water curing solution was prepared at 20 times the concentration of natural karst water. According to investigations, chloride (Cl^-), bicarbonate (HCO_3^-), and sulfate (SO_4^{2-}) are the primary aggressive ions in karst water affecting grouted matrices. Referencing groundwater monitoring data from a karst-area dam in Hunan Province, Table 1 lists the normal and accelerated concentrations of these three ions.

The curing solution was prepared using sodium chloride, sodium bicarbonate, and potassium sulfate, with an analytical purity of $\geq 99\%$. Based on calculations of ion concentration, each liter of the prepared karst water curing solution contained 1.52 g of sodium chloride, 8.91 g of sodium bicarbonate, and 21.61 g of potassium sulfate. A self-made accelerated curing box was utilized to accelerate the erosion and deterioration of the stone test block. A small heater was placed at the bottom of the curing box to control the temperature of the karst water, which was set to 30°C within a control range of 20°C–35°C. The accelerated karst water erosion test is shown in Figure 4.



2.3 Testing methods

To investigate the degradation of physical and mechanical performance in CGS (Group A) and CCGS (Group B) specimens under karst water erosion, we conducted analyses of compressive strength, porosity, mass loss, and scanning electron microscopy (SEM) on pre-prepared specimens. The tests adhered to the technical code for testing in China (Ministry of Transport of the People's Republic of China, 2019; Ministry of Construction of the People's Republic of China, 2019). A summary of the experimental design, including test conditions, is presented in Table 2. The procedures were as follows.

- (1) Specimen preparation and curing. CGS and CCGS specimens were cast, then placed in water-filled tanks for standard

curing under controlled conditions (temperature: $20^{\circ}\text{C} \pm 1^{\circ}\text{C}$, humidity: $\geq 95\%$) for 28 days.

- (2) Testing. After 28 days of curing, initial properties, including compressive strength, porosity, mass, and microstructural morphology, were evaluated.
- (3) Accelerated erosion exposure. Specimens were transferred to a temperature-controlled accelerated erosion chamber ($30^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$) for grouped curing periods of 30, 60, 90, and 120 days.
- (4) Post-erosion evaluation. Post-curing tests replicated baseline measurements to quantify degradation metrics: compressive strength loss (%), porosity increase (%), mass loss (%), and microcrack evolution (SEM).



3 Results

3.1 Analysis of compressive strength test results

The compressive strength test results for grouted stones under accelerated karst water erosion are summarized in Figure 5. With prolonged curing time, the compressive strength of CGS (Group A) decreased from 32.89 MPa to 20.03 MPa, while CCGS (Group B) declined from 3.89 MPa to 2.03 MPa. Notably, Group A exhibited significantly higher strength than Group B. This difference stems from the charge interaction in cement-clay grout: positively charged cement hydration particles partially exchange charges with clay particles, inducing clay agglomeration to form a gel-structured skeleton. However, this skeleton demonstrates inferior mechanical performance compared to the robust particle skeleton created by cement hydration (Feng, 2015). Furthermore, both groups experienced progressive strength reduction over time due to chemical erosion from karst water. The dissolution of calcium hydroxide and degradation of hydration products (e.g., calcium silicate hydrate and calcium aluminate hydrate) into less cohesive compounds gradually compromised the structural integrity of the grouted stones, diminishing their load-bearing capacity (Zhou et al., 2022).

Figure 6 illustrates the reduction rates of compressive strength for Groups A and B grouted stones. After 120 days of curing in a karst water environment, Group A exhibited a strength reduction rate of 39.10%, while Group B showed a higher reduction rate of 47.67%, indicating that Group A experienced less strength degradation compared to Group B. This disparity arises because cement particles, with their coarser size and superior cementation properties, form a more stable granular

skeleton structure in cement grout (Xie et al., 2025). This enhanced stability mitigates strength deterioration in cement grout stones relative to cement-clay grout, where the weaker clay-cement matrix is more susceptible to karst water erosion. These results further confirm that cement-clay materials exhibit inferior resistance to karst water erosion compared to pure cement materials (Bai, 2001).

Additionally, Figure 7 depicts the compressive failure morphology of grouted stone specimens cured in karst water for varying durations. Unconfined compressive strength tests revealed that failure occurred through a progressive crack propagation process: cracks initiated at the base and outer surfaces, extended upward and inward, and ultimately coalesced to cause specimen failure. The crack orientation aligned predominantly with the axial loading direction. Notably, no significant shear failure was observed during the entire unconfined compression process, demonstrating that structural disintegration was driven primarily by tensile splitting rather than shear mechanisms.

3.2 Analysis of porosity test results

Figure 8 shows the porosity test results of grouted stone specimens under different accelerated karst water erosion conditions. With the increase in curing time, the porosity of Group A increased from 26.06% to 33.91%, while that of Group B increased from 58.04% to 77.01%. The porosity of Group B was significantly higher than that of Group A. This is because the cement-based grouting material used in Group A exhibited better fluidity and higher density compared to the clay-cement grouting material in Group B. The porosity of both Groups A and B increased with curing time. The primary reason is that in the karst water environment, calcium hydroxide ($\text{Ca}(\text{OH})_2$) within the grouted stones dissolves and reacts with erosive ions, reducing its concentration in the surrounding water. This process accelerates the decomposition and dissolution of other hydration products, resulting in continuous loss of chemical substances and gradual enlargement of pores within the grouted stones (Tang, 2019).

As shown in Figure 9, after 120 days of curing in the karst water environment, the porosity increase magnitude of Group A reached 30.12%, while that of Group B was 32.68%. The smaller variation in Group A's porosity aligns with its lower strength reduction compared to Group B, and the underlying mechanisms are similar. Additionally, it was observed that the porosity growth rates of both groups were relatively slow during the first 90 days of curing. However, after 90 days, the rates accelerated. This phenomenon can be attributed to calcium hydroxide being the primary dissolved component in the early stage. As pores enlarged and increased, the contact area between various hydration products and karst water increased, accelerating the dissolution and erosion rates of calcium hydroxide and other hydration products, thereby hastening porosity growth (He, 2019). Pore structure and thermal behavior of subsurface materials have been extensively modeled to assess effective thermal conductivity and degradation behavior (Rizvi et al., 2020b).

TABLE 1 Ion concentration of karst water curing solution.

Number	Ions	Normal concentration (mmol/L)	20x concentration (mmol/L)
1	Chloride (Cl^-)	1.3	26
2	Bicarbonate (HCO_3^-)	5.3	106
3	Sulfate (SO_4^{2-})	6.2	124

TABLE 2 Design of physical-mechanical tests for grouted stone under accelerated erosion by karst water.

Number	Test type	Test method	Test conditions
1	Compressive strength	Hydraulic testing machine	(1) Tests were conducted after 28 days of maintenance under standard conditions (initial state) (2) Based on the first condition, place the specimens into a karst water accelerated erosion environment for testing at the following intervals: 30 days, 60 days, 90 days, and 120 days
2	Porosity	Weighing	
3	Mass loss	Weighing	
4	Microstructure testing	Scanning electron microscope (SEM)	

Note: For the mass loss test, clear water curing for 30d, 60d, 90d and 120d were added for comparison test.

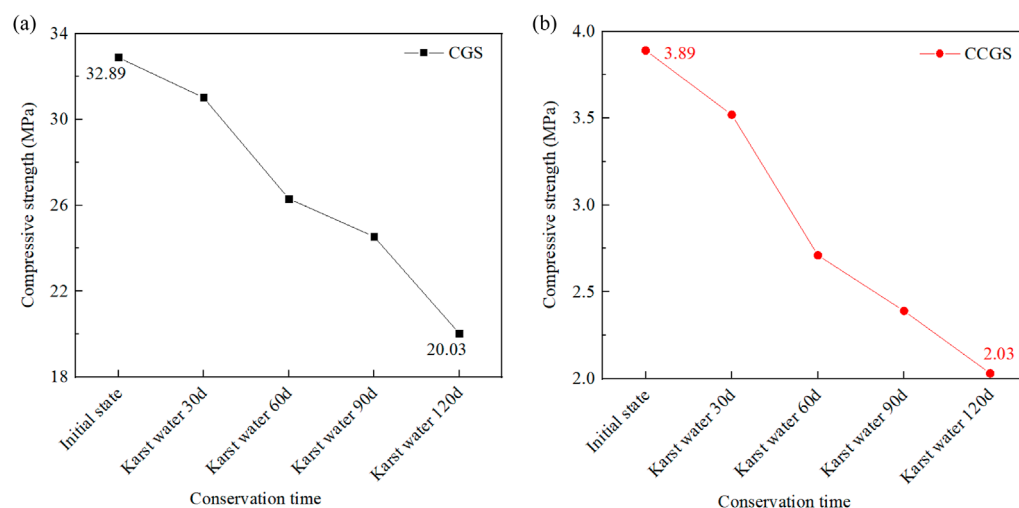


FIGURE 5

Compressive strength results of grouted stones under karst water erosion: (a) CGSs (Group A); (b) CCGSs (Group B).

3.3 Analysis of the results of the grouted stone mass test

The experimental study on grouted stone body specimens cured in clear water and karst water environments revealed distinct mass variation trends over different periods (as shown in Figure 10). Prior to 60 days of curing, the mass change rates of Groups A and B showed minimal differences between the two environments. However, beyond 60 days, specimens in karst water exhibited significantly greater mass variations compared to those in clear water, with the divergence amplifying over time, indicating accelerated deterioration effects from karst water. At 150 days, Group A specimens demonstrated mass change rates of 3.00%

(clear water) and 4.50% (karst water), while Group B reached 4.63% and 6.44%, respectively. Notably, Group B consistently displayed higher mass variation rates than Group A. Early-stage chemical reactions between erosive ions in karst water and hydration products (e.g., calcium hydroxide dissolution) initially reduced specimen mass. However, subsequent formation of expansive minerals like gypsum and ettringite partially filled pore structures, temporarily offsetting mass loss through physical expansion while retarding further dissolution. For Group A specimens, this expansive filling initially outweighed dissolution effects, causing a slight mass gain. Prolonged exposure ultimately weakened cementitious bonding, inducing surface softening and edge spalling in both groups, thereby gradually reversing the mass trends.

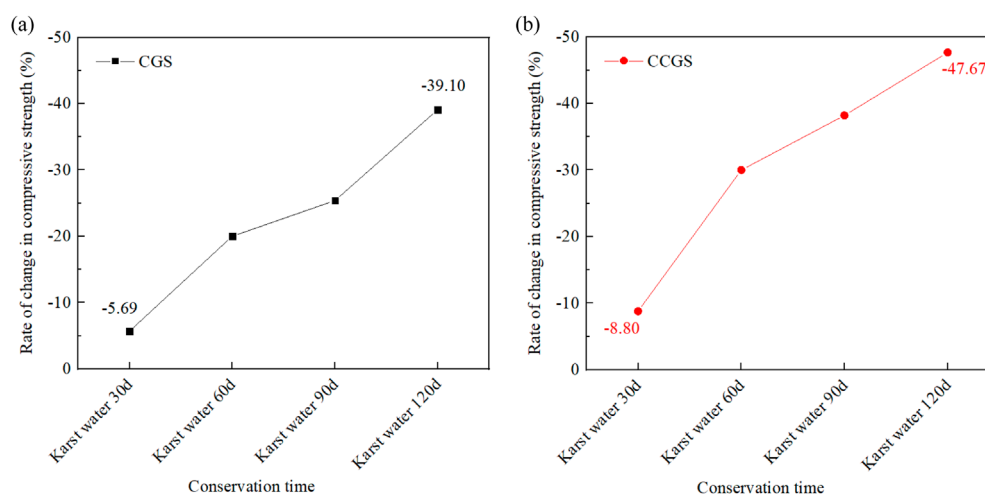


FIGURE 6
Degradation trends of compressive strength in grouted stones under karst water erosion: (a) CGSs (Group A); (b) CCGSs (Group B).

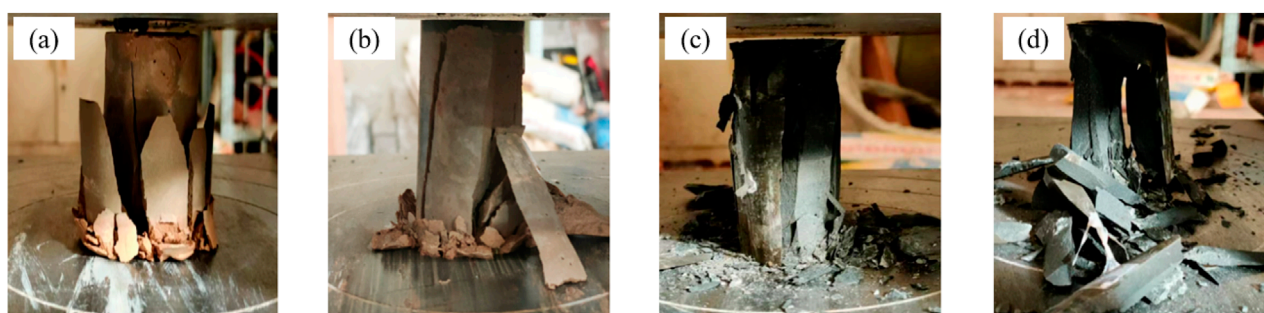


FIGURE 7
Failure mode of grouted stones under compression: (a) CGS cured for 28d under standard conditions; (b) CCGS cured for 28d under standard conditions; (c) CGS after 60 days of karst water erosion; (d) CCGS after 60 days of karst water erosion.

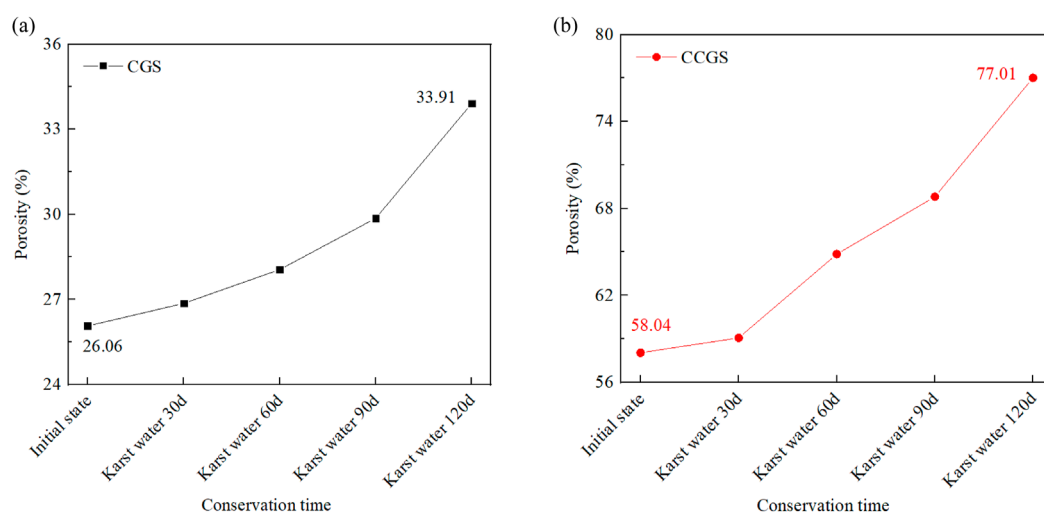


FIGURE 8
Porosity results of grouted stones under karst water erosion: (a) CGSs (Group A); (b) CCGSs (Group B).

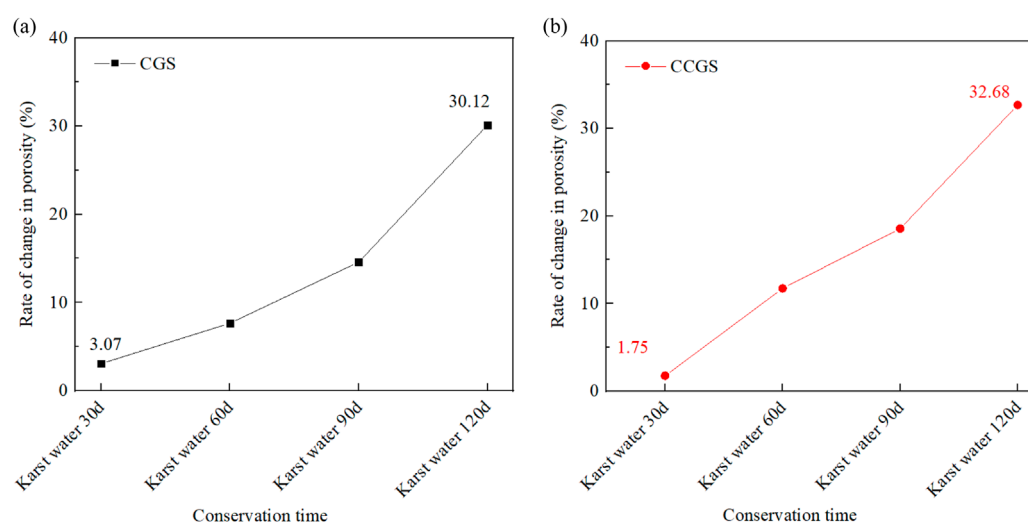


FIGURE 9
Porosity variation of grouted stones under karst water erosion: (a) CGSs (Group A); (b) CCGSs (Group B).

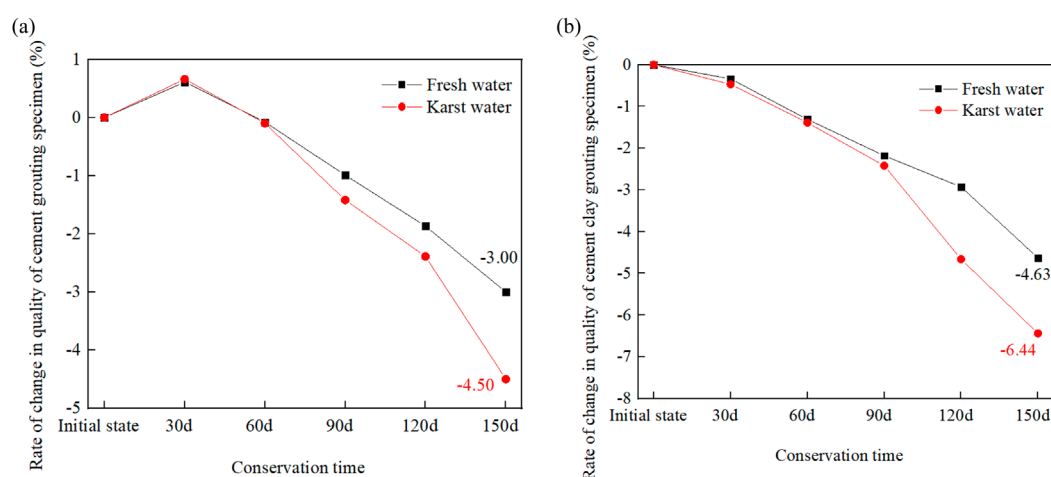


FIGURE 10
Mass loss rate of grouted stones under fresh and karst water erosion: (a) CGSs (Group A); (b) CCGSs (Group B).

Underground structural performance also varies with geometric and geomechanical parameters, as seen in tunnel stability studies (Alsabhan et al., 2021).

4 Discussion

Microstructural morphology serves as a critical indicator for reflecting changes in the internal composition and pore structure of grouted stones. SEM analysis was conducted on specimens cured for varying durations under karst water erosion. As shown in Figures 11, 12, the cement-grouted stone specimens (Group A) exhibited a dense structure with sufficient hydration, abundant C-S-H gels, and layered calcium hydroxide (irregular hexagonal flakes), along with minor calcium carbonate (blocky formations).

In contrast, the CCGS (Group B) showed reduced cement content due to clay incorporation. Their microstructure revealed cement hydration products enveloped by clay particles, limited exposed cementitious materials, and sparse calcium hydroxide crystals and ettringite (needle-shaped). Notably, Group B specimens displayed distinct pores and microcracks, resulting in higher porosity and lower strength compared to Group A, macroscopic analysis revealed that Group A exhibited a compact microstructure, whereas Group B demonstrated pronounced porosity, consistent with macroscopic test results. Lattice element methods further enable accurate simulation of thermal transport and its relationship to geomaterial integrity (Rizvi et al., 2018).

Figures 12, 13 illustrate that after 60 days of karst water erosion, chemical reactions within the grouted stones generated secondary products such as calcium carbonate, gypsum, and

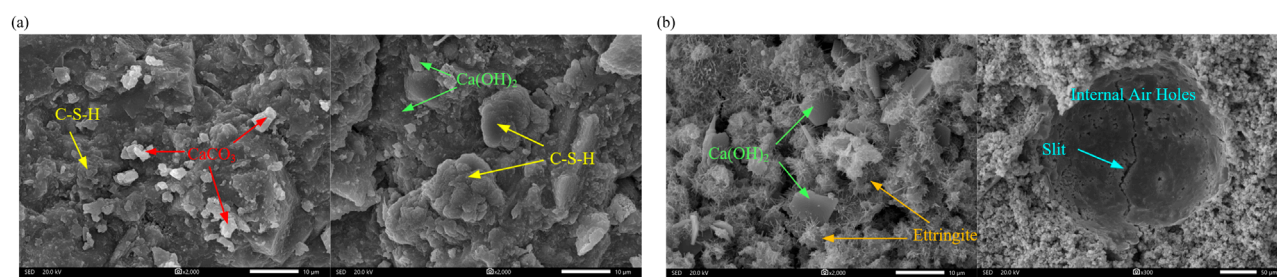


FIGURE 11
Micro-morphology of grouted stones for 28d under standard conditions (initial state): (a) CGSs (Group A); (b) CCGSs (Group B).

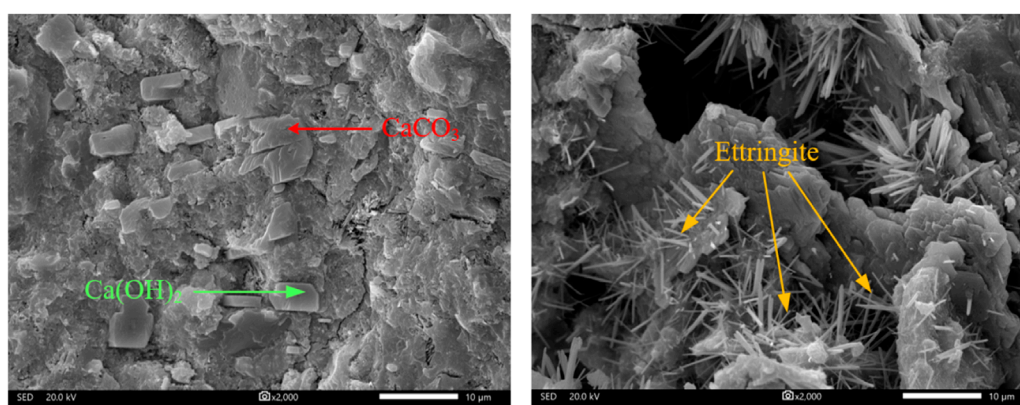


FIGURE 12
Micro-morphology of CGSs for 60d under karst water erosion.

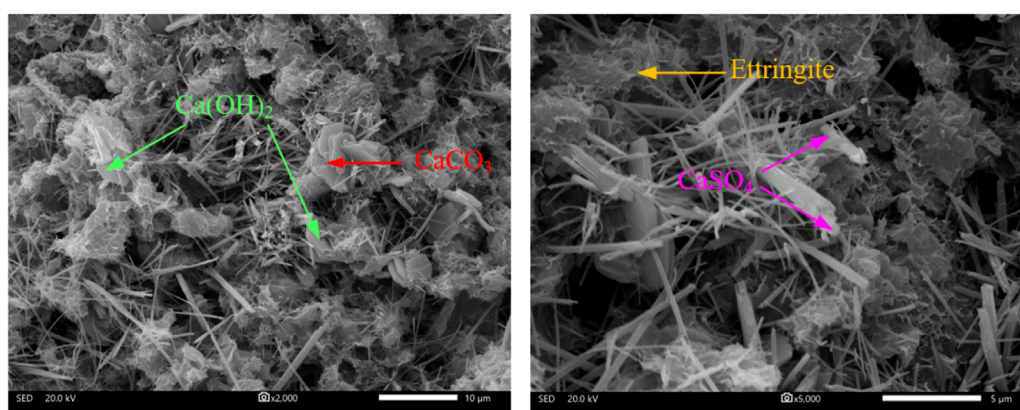


FIGURE 13
Micro-morphology of CCGSs for 60d under karst water erosion.

ettringite. Compared to the initial state after 28 days of standard curing, the 60-day eroded specimens developed pores and cracks. This deterioration arises from erosive ions reacting with calcium hydroxide to form gypsum, which subsequently interacts with aluminum phases to produce expansive ettringite. The growth of ettringite generates swelling stress at pore interfaces, fracturing the

cementitious matrix. As erosion products dissolve or detach, the grouted stones become increasingly porous and fragile, leading to altered physical-mechanical properties (e.g., compressive strength, porosity) (Yu, 2017). Environmental fluctuations such as heat and moisture changes significantly influence the microstructural evolution of underground materials (Ahmad et al., 2025).



FIGURE 14
Micro-morphology of CGSs for 120d under karst water erosion.

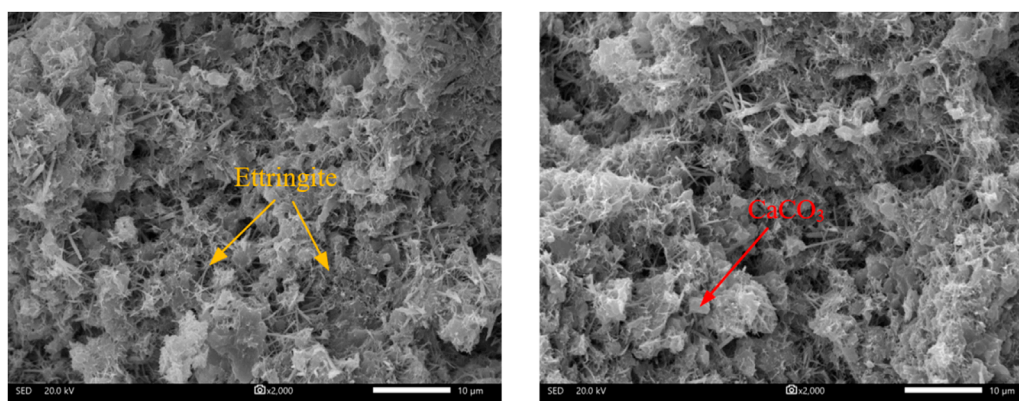


FIGURE 15
Micro-morphology of CCGSs for 120d under karst water erosion.

Figures 14, 15 demonstrate that after 120 days of karst water erosion, the grouted stones exhibited significantly increased crack density and width, indicating severe structural degradation. While calcium carbonate and gypsum continued to form, no chloride-containing compounds (e.g., calcium chloride) were detected. This absence is attributed to the low chloride ion concentration in the simulated karst water and the competitive reaction between sulfate ions (prioritized due to their higher affinity with C_3A phases) and chloride ions. Consequently, chloride-related erosion products were negligible and undetectable in the sampled specimens (Wang et al., 2022).

5 Conclusion

Compressive strength and porosity tests were conducted on cement and CCGS specimens under varying curing durations to investigate the evolution of their mechanical and structural properties. Results demonstrated that under karst water curing, both groups exhibited progressive compressive strength reduction and porosity increase. Within 120 days, CGS specimens showed

a strength decline from 32.89 MPa to 20.03 MPa, while CCGS specimens experienced a more pronounced deterioration, decreasing from 3.89 MPa to 2.03 MPa. Similarly, porosity values for CGSs rose from 26.06% to 33.91%, whereas CCGSs displayed a significantly higher porosity increase from 58.04% to 77.01% over the same period, confirming that CCGS suffered greater degradation in both strength and porosity.

Mass variation and microstructural morphology analyses were performed on cement and CCGS specimens under different curing durations and environments. Experimental findings revealed that karst water induced chemical and structural alterations in both groups through erosive effects. However, CCGSs exhibited more severe deterioration, characterized by higher mass variation rates and more drastic internal structural changes. The cement-clay matrix in CCGSs proved more vulnerable to karst water erosion, likely due to its inherently weaker cementitious bonding and higher initial porosity, which accelerated ion penetration and reaction-induced damage. The findings highlight the inferior durability of cement-clay composites under karst water conditions and provide critical insights for optimizing grouting materials in karst-prone environments.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

WT: Writing – original draft, Validation, Writing – review and editing, Data curation. MX: Writing – review and editing, Methodology, Conceptualization. XF: Writing – review and editing. CH: Writing – review and editing, Investigation. CM: Visualization, Writing – review and editing. YC: Writing – review and editing.

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Conflict of interest

Author WT was employed by Hunan Urban and Rural Environmental Construction Co., Ltd. Author CH was employed by Hunan Construction Investment Group Infrastructure Investment Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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