Study on the Evolution Law of Macroscopic Shear Behavior of Sandstone-Concrete Interface under Freeze-Thaw Cycles

Chuang SUN, Leilei JING*

College of Civil Engineering, Liaoning Technical University, Fuxin 123000, Liaoning China

*Email: jingleilei888@163.com

Abstract. In tunnel engineering in cold regions, the bond interface between surrounding rock and concrete lining is prone to deterioration under the action of freeze-thaw cycles, which seriously threatens the safety of the project. Aiming at the deterioration of sandstone-concrete interface in cold regions, the experimental study of macroscopic mechanical properties was carried out. The results show that : (1) The shear strength of the interface decreases significantly with the increase of freeze-thaw cycles, and the lower the interface roughness, the more significant the strength attenuation. Under the condition of low roughness, the maximum decrease of shear strength after 50 freeze-thaw cycles can reach 40 %. (2) Freeze-thaw action generates frost heave force through pore water, which leads to the internal damage of the material and the decrease of interfacial bond strength. The specific performance is that the peak shear stress difference between specimens with different roughness decreases continuously with the increase of freeze-thaw cycles.

Keywords: rock-concrete interface, freeze-thaw cycle, interface roughness, macroscopic mechanical properties

1 Introduction

As construction projects continuously grow in both volume and overall scale, the operational boundaries of geotechnical engineering and tunnel engineering are increasingly advancing into high-altitude frozen soil regions. The tunnel is a typical project that is particularly vulnerable to freezing damage. The structural framework's mechanical characteristics ensure stability and safety throughout the structure's lifespan. [1]. Due to the freeze-thaw effect and the compressive stress of the surrounding rock, the supporting structure is prone to shear failure. [2,3], including lining cracking, suspended icicles, side wall leakage, floor heave and concrete spalling occurred. Therefore, it is very important to fully grasp the development process of rock-concrete shear failure under F-T cycle.

Extensive investigations by numerous scholars have focused on the interfacial bond strength inherent to rock-concrete composites, successfully illuminating how surface

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irregularity acts as a primary determinant governing this mechanical capacity. Krounis et al.[4] The direct shear experiments of binary materials with different adhesion degrees were carried out, and it was found that the existence of interface protrusions significantly enhanced the cementation ability. Finally, it is concluded that different materials and different interface protrusion types have a very important relationship with the shear strength of the binary interface. Mouzannar et al.[5] have shown that the maximum shear strength of rock-concrete composite structures depends not only on the cementation strength and surface texture of rock and concrete, but also on the force applied perpendicular to the material plane. The bond strength characterizing the rock-concrete interface is continuously governed by a multitude of distinct variables.. For example, Investigations conducted by Shen Yanjun et al.[6] regarding the freeze-thaw damage experienced by sandstone-concrete composites successfully identified four primary variables that dictate the bond performance at the rock-concrete interface. These critical elements encompass the ambient external environment, the intrinsic hydrophilic and hydrophobic characteristics of the rock, the geometric roughness of the contact boundary, and the fundamental physical properties of the base materials themselves. The rock-concrete interface is a weak surface layer, and the freeze-thaw cycle mainly affects the bonding of the rock-concrete interface, which leads to the failure of the engineering protection. However, the above research does not consider the influence of temperature on the structure. In response to this problem, many scholars have carried out related research. Shen et al.[7] studied the freeze-thaw of granite-concrete, and found that the freeze-thaw cycle would lead to the decrease of interface bonding performance and deterioration of interface cementation. Zhao et al.[8] studied the effect of F-T cycle on the mechanical properties of pervious concrete. Pan et al.[9]al. systematically revealed the degradation of mechanical properties, phase evolution and microscopic debonding mechanism of sandstone-concrete interfacial transition zone under freeze-thaw cycles by nanoindentation technique combined with microstructure observation. Through the combination of laboratory test and particle flow numerical simulation, Zhang et al.[10] revealed the evolution law of macro-micro mechanical properties and shear fracture mechanism of sandstone-concrete interface under freeze-thaw cycle. Gou et al.[11] studied the crack propagation law and failure mechanism of rock-concrete composite specimens with different interface dip angles under freeze-thaw cycles and uniaxial compression through laboratory tests and PFC^{2D} numerical simulation. Wei et al.[12] conducted direct shear tests under different freeze-thaw cycles and shear rates to study the degradation laws and failure characteristics of the interface bonding strength between sandstone and concrete, and established a theoretical model for interface strength degradation that simultaneously considers the freeze-thaw effect and shear rate. Guti 'errez-Ch et al.[13] established a refined element model for direct shear test of rock-concrete interface, considering different boundary conditions. Through this model, the shear characteristics are captured in detail, the failure mode is determined, and the damage assessment of the rock-concrete interface is carried out thoroughly..

Therefore, this study selected sandstone-concrete composite materials with different interface texture features, including *JRC* values of 6.738,3.727 and 0, and various F-T cycles from $N_T = 0$ to $N_T = 60$. The variable angle shear test was carried out on them. The results reveal how the macroscopic mechanical properties change with different F-

T cycles. Then, we deeply analyzed the macroscopic mechanical behavior of the rock-concrete interface under freeze-thaw cycles.

2 Sample Preparation and Scheme Design

This study designates the sandstone-concrete interface as its primary investigative target, utilizing raw sandstone excavated directly from the tunnel site of the Jida railway project. The concrete studied is C30 concrete mixed with P.O42.5 Portland cement, sand and water. Three different surface treatments were carried out on the sandstone specimens of 100mm × 100mm × 50mm, and the influence of different surface roughness was considered. Subsequently, these samples were placed in a 100mm × 100mm × 100mm mold, and concrete was poured on the other side. After 24 hours of natural air drying, the mold was placed at a constant temperature of 20 ° C and 95 % relative humidity for 28 days to produce a sandstone-concrete interface with three roughness levels. The cubic sample is shown in Figure 1 (a). These specimens were then placed in a 100mm × 100mm × 100mm mold and filled with concrete. After 24 hours of natural air drying, the mold was placed in a constant temperature environment of 20 °C and 95 % relative humidity for 28 days to produce three roughness grades of sandstone-concrete interface. The cubic specimen is shown in Figure1 (a). The groove spacing is no groove ($JRC = 0$), 20mm ($JRC = 3.727$) and 15mm ($JRC = 6.738$), respectively. To quantitatively evaluate the surface roughness, our study adopted the trace length method [14], with the exact mathematical procedure detailed in Equations (1).

$$JRC = 1979 R_p^{0.92} \varepsilon^{1.46} \quad (1)$$

Subsequently, the sandstone-concrete sample was immersed in a water-containing vacuum dish, and was completely immersed and sealed for 4 ~ 6h to drain the air in the pores of the specimen, and the vacuum state was maintained for 4 ~ 6h to fully absorb water and saturate. After saturation, the samples were subjected to F-T cycle. Dictated by the actual climate conditions recorded at the construction location, the F-T temperature parameters were strictly regulated at -20 °C and -20 °C. A single F-T weathering phase required exactly 24 hours to complete. As systematically mapped out in Figure 1 (b), the test specimens were subsequently evaluated after enduring 0,20,30,40 and 50 respective F-T cycles.

In order to determine the shear strength of sandstone-concrete composites, 45° oblique shear method was used in the test. Using TAW2000 mechanical test system, the loading program adopts displacement control mode and runs at a strict control rate of 0.1 mm / min. In addition, the sensor adjustment mechanism ensures that the load accuracy is maintained within a safe range of ± 0.5 %, as shown in Figure 1 (c).

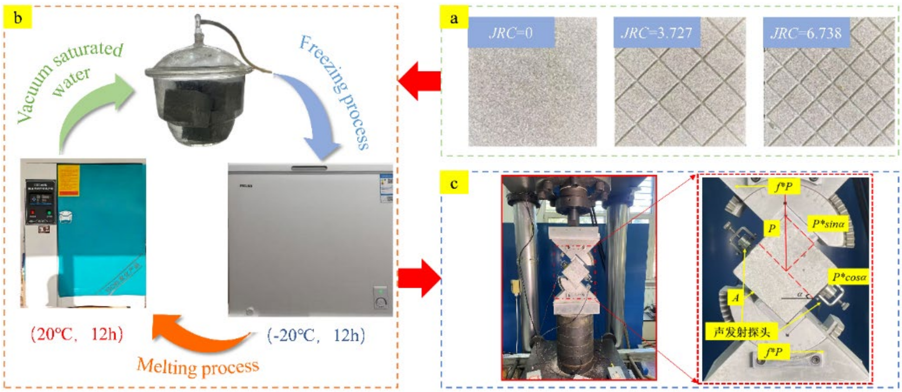


Fig. 1. Sandstone-concrete sample preparation and shear test equipment

3 Test Result and Analysis

3.1 Sandstone-Concrete Interface Shear Test Results

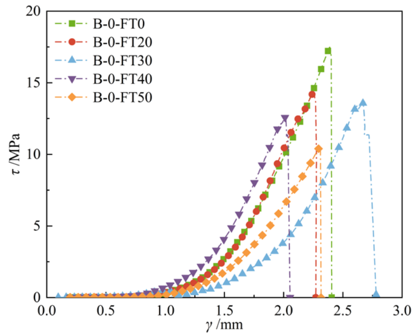
In this research, we applied the 45 ° variable angle shear method as our primary analytical technique for determining the shear strength of the sandstone-concrete interface. Based on the experimental data recorded by the electro-hydraulic servo universal testing machine, we computed the shear stress-strain curve for every individual specimen in accordance with Equations. (2). The resulting graphical representations are clearly depicted in Figure 2.

$$\begin{cases} \tau = \dfrac{P}{A}\sin\alpha, & \varepsilon_\tau = S\sin\alpha \\ \sigma = \dfrac{P}{0.9A}\cos\alpha, & \varepsilon_\sigma = S\cos\alpha \end{cases} \tag{2}$$

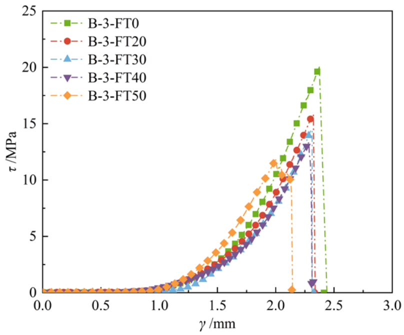
Where τ is shear stress ; σ is normal stress ; P is vertical pressure ; A is the bonding area of the sample. Because the fixture is not completely covered in the direction of normal stress, 0.9A is used in this study. α is the shear angle, which is set to 45 ° in this study. The shear displacement and axial displacement are respectively ε_τ、ε_σ ; S is vertical displacement.

Calculated via Equation (2) using raw electro-hydraulic servo universal testing machine data, the shear stress-strain curves (Figure 2) are dictated by interface roughness and F-T cycles, evolving through four distinct phases. First, the initial densification stage forms a nonlinear concave trajectory as inherent pores and F-T induced microcracks compress. Second, the linear elastic deformation stage emerges, reflecting the concrete's cohesive shear resistance. Third, during the plastic deformation stage (or yield phase), this cohesion fails and interface roughness dominates the shear resistance; consequently, rougher sandstone-concrete boundaries exhibit more pronounced yielding. Finally, surpassing the peak shear strength triggers the failure stage—an abrupt brittle shear fracture that immediately halts data acquisition. Crucially, internal pore compaction drives the localized stress fluctuations seen along the curve, manifesting as instantaneous stress drops coupled with strain surges.

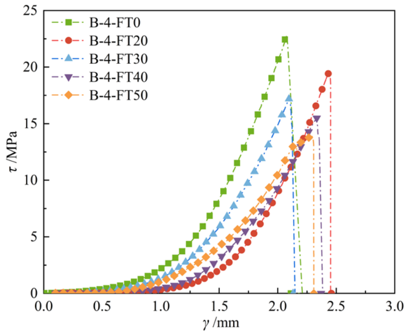
The concurrent escalation of interface roughness and freeze-thaw cycles significantly broadens the evaluated sample's shear range while exacerbating the degree of fragmentation along its failure surface. Mechanistically, this severe structural breakdown is driven by cyclic pore water phase transitions. The resulting frost heaving force enacts a dual penalty: it fractures the internal microstructures of both sandstone and concrete (diminishing inherent interface strength) and simultaneously provokes boundary debonding. This physical detachment directly strips away vital bonding force and friction, ultimately collapsing the boundary's overall bearing capacity.



(a) *JRC*=0



(b) *JRC*=3.727



(c) *JRC*=6.738

Fig. 2. Shear stress-shear strain curves of sandstone-concrete interface under different interface roughness

3.2 Peak Strength Analysis of Sandstone-Concrete Interface

According to Fig.3, the peak shear stress at the sandstone-concrete interface consistently drops as F-T cycles accumulate or interface roughness decreases. This confirms that F-T weathering inherently degrades the material's deformation resistance, while smoother contact surfaces supply less boundary friction, both ultimately resulting in diminished shear strength. Quantifying this structural damage, the F-T mechanism suppressed the specimens' shear strength by 17.41 %, 22.36 %, 27.73 %, and 40 %, respectively. Furthermore, progressive F-T loading continuously contracted the peak shear stress discrepancy between roughness values 0 and 6.738, shrinking it from an original 5.31 MPa to 5.16 MPa, 3.73 MPa, 2.86 MPa, and 3.43 MPa. As F-T cycles accumulate, the governing role of interface roughness over shear strength diminishes steadily. This weakening stems from two concurrent mechanisms: F-T damage fundamentally compromises the base material's structural integrity, while expansion from the frost heaving force triggers localized debonding across the contact zone. Ultimately, this physical separation strips away critical friction and bonding forces, rendering the initial roughness largely ineffective.

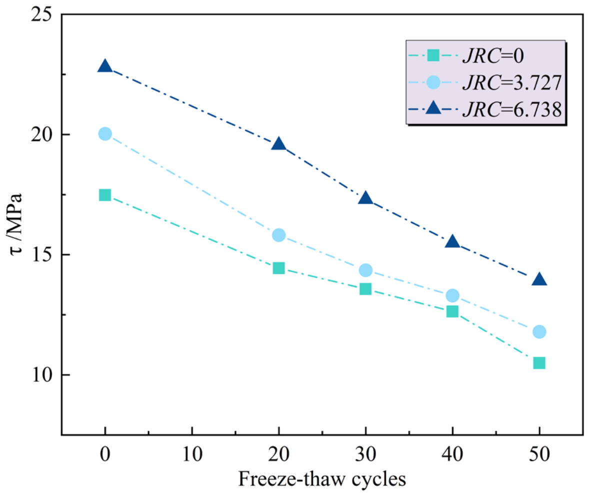


Fig. 3. Relationship between shear strength and F-T cycles

4 Conclusion

(1) Both shear stiffness and shear strength steadily decline as F-T cycles escalate and interface roughness decreases. Specifically, extreme F-T exposure severely slashed shear strength by 17.41 %, 22.36 %, 27.73 %, and 40 %, whereas elevating boundary roughness effectively countered this decay, recovering structural capacities by 12.39 % and 32.7 %.

(2) The attenuation of shear strength at the sandstone-concrete interface during the freeze-thaw cycle is primarily governed by a coupled destructive mechanism: material damage and interface debonding. Specifically, the repeated phase transitions of trapped pore water generate a disruptive frost heaving force. This expansive stress simultaneously fractures the internal microstructures of the bulk materials (lowering their baseline strength) and triggers boundary debonding (which neutralizes critical bonding force and friction force). Ultimately, the synergy of these two degradation pathways guarantees the persistent deterioration of the boundary's overall shear performance.

(3) Although interface roughness fundamentally enhances sandstone-concrete shear strength, accumulating freeze-thaw cycles severely degrade this friction-based structural advantage. Evidencing this boundary deterioration, the measurable discrepancy in peak shear stress separating highly textured specimens from smooth ones collapses continuously from an original 5.31 MPa down to 3.43 MPa. This indicates that freeze-thaw damage not only reduces the interfacial bond strength through material degradation and interfacial debonding, but also directly causes the friction provided by roughness to attenuate with freeze-thaw cycles.

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