International Society for Rock Mechanics and Rock Engineering
Macedonian Association for Geotechnics

ISRM Regional Symposium
Eurock 2026
Risk Management in Rock Engineering
Skopje, 15-19 September

DOI: https://doi.org/10.68732/0e92e7af6d3e863e
ISBN: 978-9989-2053-6-1

Exposure Time Dependency of Freeze and Thaw Damage on Hard Rocks

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Abstract

Under extreme weather conditions, freeze–thaw (FT) cycles have the potential to compromise the long-term stability of surface and underground rock structures. Pore pressure induced by volumetric expansion of water leads to crack formation through debonding of mineral grains. Although various studies have explored the correlation between the number of cycles and the degradation of mechanical parameters, the influence of FT cycle rate on damage evolution under equivalent exposure durations has received limited attention. This study investigates the short- and long-term effects of slow and fast FT cycles on the mechanical properties of andesite, selected to represent hard rock behavior. Each cycle follows a temperature path between −20 °C and +10 °C, lasting one week under the slow FT regime and 5.5 hours under the fast FT regime. Exposure durations of 2 weeks and 4 weeks were applied under both regimes to enable direct comparison at equivalent total durations. Static deformability tests were conducted for both FT regimes, while triaxial compression and indirect tensile (Brazilian) tests were performed exclusively on slow FT specimens. The results indicate that FT cycle rate plays an important role in stiffness degradation: slow FT specimens exhibit no significant change in Young's modulus, whereas fast FT conditioning induces a progressive reduction of approximately 33% over 4 weeks. These findings highlight the need to consider thermal cycling rate alongside total exposure duration in durability assessments of rock structures in cold-region engineering applications.

Keywords

Freeze and thaw damage, Experimental rock mechanics, Cold-region rock engineering.

1 Introduction

Freeze–thaw (FT) weathering represents a predominant environmental process governing the mechanical degradation of rock masses in cold and alpine climatic conditions. The repeated freezing and thawing of pore water induces volumetric expansion during freezing, generating local stresses within pores and pre-existing microcracks that promote crack initiation and propagation (Chen et al. 2004; Takarli et al. 2008). These microstructural damage mechanisms progressively reduce the stiffness, strength, and durability of rocks, with direct consequences for the long-term performance of slopes, tunnels, shafts, and mine openings in cold-region engineering (Park et al. 2015; Mutlutürk et al. 2004).

Prior experimental studies have documented reductions in uniaxial compressive strength, tensile strength, elastic modulus, and wave velocity across a range of lithologies including sandstone, granite, and andesite (Tan et al. 2011; Khanlari et al. 2015; Momeni et al. 2016; Yavuz 2011). In the majority of these investigations, damage accumulation is correlated with cycle count, while the influence of cycle duration and temperature transition rate on mechanical degradation has received limited systematic attention.

Theoretical models of FT rock fracture identify coupled ice-pressure, moisture redistribution, and crack propagation processes as primary controls on damage (Walder and Hallet 1985), yet the influence of thermal cycle rate on hard volcanic rocks remains poorly constrained.

Andesite is a volcanic rock of particular relevance to cold-region engineering; its low porosity may confer greater resistance to frost-induced damage compared to sedimentary rocks, yet its mechanical response under contrasting FT cycle rates remains poorly characterized (Mal'a et al. 2022; Yavuz 2011). Understanding this response has direct implications for the long-term performance of rock structures in mountainous terrains and underground openings subject to operational thermal cycling.

2 Materials and Methods

2.1 Sample Preparation

Andesite was selected as the test material to represent hard rock behavior under freeze–thaw (FT) conditions. All specimens were prepared from intact, massive rock blocks to minimize material heterogeneity. Specimen preparation and testing were conducted in accordance with the relevant ISRM suggested methods for deformability, triaxial compression, and indirect tensile testing. Cylindrical specimens with a diameter-to-length ratio of 2.5 were prepared for deformability and triaxial compression tests, while disk-shaped specimens were prepared for indirect tensile (Brazilian) tests.

2.2 Freeze–Thaw Cycling Procedure

Two FT conditioning regimes were applied, both following the same temperature range (+10 °C to −20 °C to +10 °C). The slow FT regime consisted of cycles lasting one week (168 hours) each, with 12 temperature steps of 14 hours each. The fast FT regime consisted of cycles lasting 5.5 hours each, with 12 variable-duration steps covering the same range. Slow FT specimens were subjected to 2 and 4 cycles; fast FT conditioning was applied at approximately 30, 60, 90, and 120 cycles, with only the 60-cycle (2-week equivalent) and 120-cycle (4-week equivalent) groups included in the comparative mechanical test program.

Table 1. Summary of freeze–thaw conditioning regimes and specimen distribution across mechanical test types. All regimes follow a temperature range of −20 °C to +10 °C.

FT Regime	Cycle Rate	Exposure Duration	No. of Cycles	Cycle Duration
NC (Unconditioned)	–	–	0	–
Slow FT	Short	2 weeks	2	1 week
Slow FT	Long	4 weeks	4	1 week
Fast FT	Short	2 weeks	60	5.5 h
Fast FT	Long	4 weeks	120	5.5 h

* Fast FT conditioning was also applied at 30 and 90 cycles (1 and 3 weeks); these exposure levels are excluded from the comparative test program.

Each test group comprised 3–4 specimens for static deformability testing; slow FT and unconditioned groups were additionally tested with 3 specimens under triaxial compression and 4 under indirect tension.

3 Results and Analysis

3.1 Variation of Stiffness with Exposure to Different Freeze–Thaw Regimes and Durations

The static deformability test results reveal a pronounced divergence in the mechanical response of andesite between slow and fast FT conditioning regimes (Fig. 1).

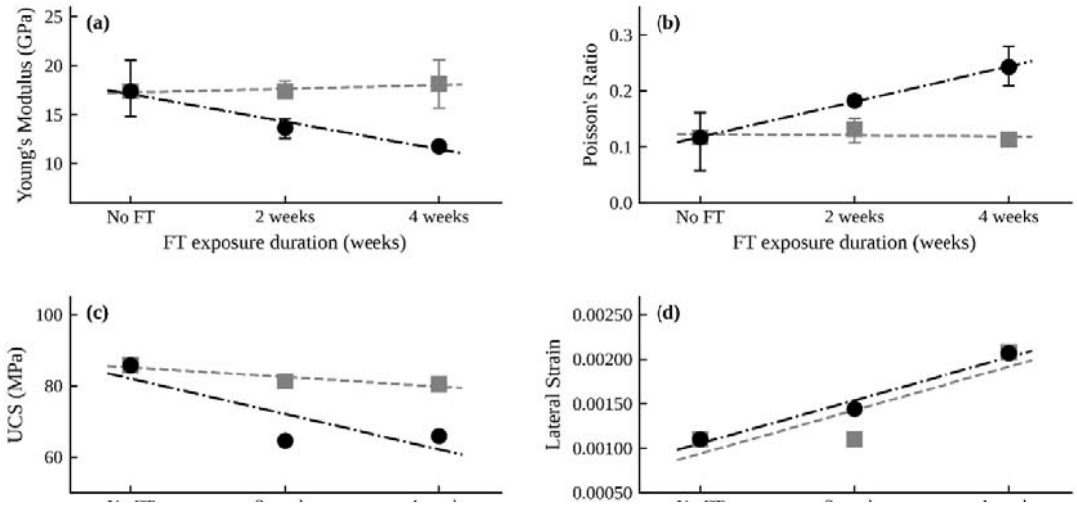


Fig. 1 Static deformability test results for slow and fast FT specimens at equivalent exposure durations: (a) Young's modulus, (b) Poisson's ratio, (c) uniaxial compressive strength (UCS), and (d) lateral strain.

The average Young's modulus of unconditioned specimens is approximately 17.5 GPa. Specimens subjected to slow FT cycles show no significant change with increasing exposure duration, with the modulus remaining approximately 17.5 GPa after 2 weeks and marginally rising to approximately 18.0 GPa after 4 weeks, a variation well within experimental scatter (Fig. 1a). In contrast, fast FT conditioning induces a progressive and substantial reduction in Young's modulus, decreasing to approximately 13.8 GPa after 2 weeks and further to approximately 11.8 GPa after 4 weeks, corresponding to a total reduction of approximately 33% relative to the unconditioned state. The approximately linear trend observed in the fast FT group indicates a consistent, accumulative stiffness loss driven by the higher rate of thermal cycling.

Uniaxial compressive strength (UCS) results follow a pattern consistent with the Young's modulus data (Fig. 1c). Unconditioned and slow FT specimens yield comparable UCS values of approximately 85 MPa, with slow FT exposure producing only a minor reduction to approximately 80 MPa after 4 weeks. Fast FT specimens exhibit a more pronounced decrease from approximately 86 MPa to approximately 65 MPa after 2 weeks, corresponding to a total reduction of approximately 24%, with values remaining similarly reduced at 4 weeks.

Poisson's ratio follows a complementary pattern (Fig. 1b). Slow FT specimens maintain a nearly constant Poisson's ratio throughout exposure (0.11–0.13). Fast FT specimens exhibit a progressive increase from approximately 0.12 to 0.245 over 4 weeks, accompanied by a substantially steeper increase in lateral strain relative to slow FT specimens at equivalent durations (Fig. 1d), confirming a consistent pattern of enhanced transverse deformability in fast FT specimens.

3.2 Variation of Strength under Confinement with Exposure to Different Freeze–Thaw Durations

The triaxial compression test results indicate that freeze–thaw cycling modifies the strength of andesite under confined loading conditions. Failure stresses increase with confining pressure for all specimen groups, confirming a friction-controlled failure mechanism. However, the slope and intercept of the failure envelopes vary systematically with freeze–thaw exposure (Fig. 2).

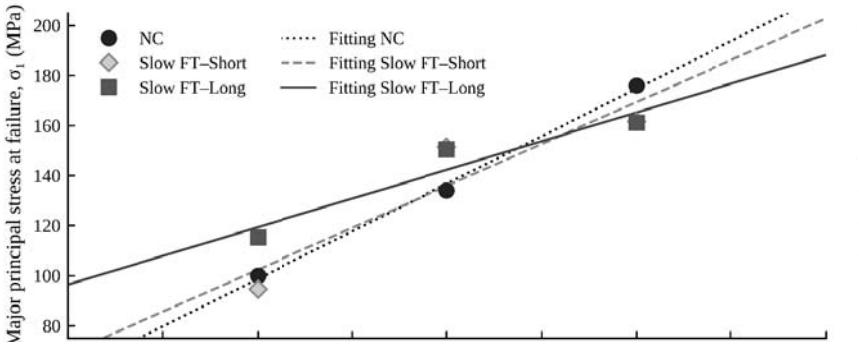


Fig. 2 Triaxial failure envelopes for unconditioned (NC) and slow FT-conditioned andesite specimens tested at confining pressures of 5, 10, and 15 MPa.

For unconditioned specimens, the fitted failure envelope yields a friction angle of approximately 50° and an apparent cohesion of approximately 11 MPa. After short-term slow freeze–thaw exposure, the friction angle decreases to approximately 48°, while apparent cohesion increases to approximately 13 MPa. With long-term exposure, the friction angle further decreases to approximately 40°, accompanied by a marked increase in apparent cohesion to approximately 22 MPa.

The reduction in friction angle suggests progressive degradation of grain interlocking and surface roughness due to freeze–thaw-induced microcracking. In contrast, the increase in apparent cohesion reflects a confinement-dependent response, likely associated with microcrack closure and stress redistribution during triaxial loading rather than intrinsic strengthening of the rock matrix.

3.3 Variation of Tensile Strength with Exposure to Different Freeze–Thaw Durations

The indirect tensile test results demonstrate a sensitivity of tensile strength to freeze–thaw exposure (Fig. 3). The average Brazilian tensile strength of unconditioned specimens is approximately 9.6 MPa. After 2 weeks of slow freeze–thaw cycling, the average tensile strength decreases to approximately 8.9 MPa, corresponding to a reduction of about 7%. Following 4 weeks of exposure, the tensile strength partially recovers to approximately 9.2 MPa, although it remains slightly below the unconditioned level.

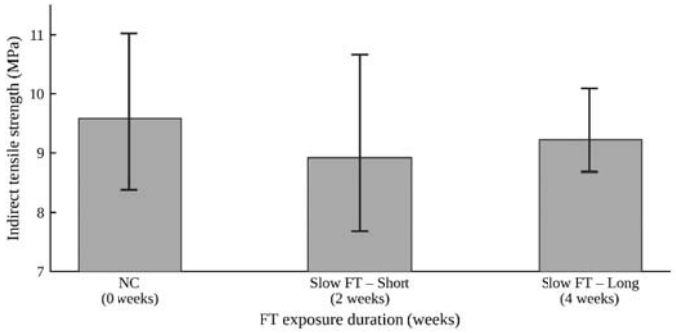


Fig. 3 Indirect tensile (Brazilian) test results for NC and slow FT-conditioned andesite specimens.

4 Discussion

4.1 Interpretation of Freeze–Thaw-Induced Mechanical Degradation

The experimental results indicate that FT cycle rate, in addition to total exposure duration, plays a governing role in andesite stiffness degradation. While slow FT specimens show no clear reduction in Young's modulus at either exposure duration, fast FT conditioning induces a progressive reduction from approximately 17.5 GPa to 11.8 GPa over 4 weeks, corresponding to a loss of approximately 33%. This divergence suggests that the accumulation of thermally induced microstructural damage is controlled not only by cumulative exposure time but also by the frequency of thermal transitions.

The contrasting behavior between the two regimes may be interpreted in terms of time-dependent damage mechanisms operating at the pore and microcrack scale. Under slow FT cycling, the extended duration of each thermal stage may allow partial stress relaxation, moisture redistribution, and limited crack arrest before the subsequent thermal transition. Under fast FT cycling, the rapid succession of

thermal loads may promote repeated crack initiation, propagation, and coalescence within the same exposure period. This interpretation is broadly consistent with the theoretical framework of Walder and Hallet (1985), in which frost-induced crack growth is controlled by coupled ice-growth and water-supply processes at crack tips.

The Poisson's ratio and lateral strain results reinforce this interpretation (Fig. 1b, 1d). Slow FT specimens maintain an approximately constant Poisson's ratio with only modest lateral strain increase, consistent with the absence of stiffness degradation. Fast FT specimens exhibit a monotonic increase to 0.245, with substantially higher lateral strain values, reflecting progressive microcrack development under accelerated thermal cycling (Brace et al. 1966; Jaeger et al. 2007).

The triaxial compression results indicate that slow FT exposure modifies strength parameters even though the static deformability tests did not show a clear reduction in Young's modulus. The reduction in friction angle from approximately 50° to 40° with increasing slow FT duration (Fig. 2) suggests progressive degradation of grain interlocking and frictional resistance along micro-discontinuities, consistent with friction-controlled failure models (Paterson and Wong 2005). The concurrent increase in apparent cohesion from approximately 11 MPa to 22 MPa reflects a confinement-dependent response associated with crack closure under higher confining pressures (Brace et al. 1966; Jaeger et al. 2007) rather than intrinsic material strengthening.

4.2 Implications for Rock Engineering Applications

The indirect tensile test results (Fig. 3) reveal that tensile strength is sensitive to slow FT exposure, with a reduction of approximately 7% observed after short-term conditioning. Following 4 weeks of exposure, the tensile strength partially recovers to approximately 9.2 MPa, although the mechanism remains ambiguous and warrants dedicated microstructural investigation in future work. Compared with compressive behavior, the tensile response is more sensitive to freeze–thaw damage, confirming that crack-controlled failure mechanisms dominate under indirect tensile loading.

These findings are relevant to rock structures exposed to artificial or operational thermal cycling. In such applications, cycle rate may be as consequential as total exposure duration, and design frameworks should account for thermal cycling rate alongside conventional strength-based criteria.

5 Conclusions

This study presents a systematic experimental investigation of the combined effects of FT cycle rate and exposure duration on the mechanical behavior of andesite, through static deformability tests conducted under both slow and fast FT regimes, and triaxial compression and indirect tensile testing conducted under the slow FT regime. Based on the experimental results, the following conclusions are drawn:

1. Slow and fast FT cycling produce markedly different stiffness responses at equivalent exposure durations. Fast FT conditioning induces a progressive ~33% reduction in Young's modulus (17.5 to 11.8 GPa over 4 weeks), a monotonic increase in Poisson's ratio from 0.12 to 0.25, higher lateral strain values, and a ~24% UCS reduction, while slow FT specimens show no significant change in any of these parameters.
2. Slow FT cycling systematically modifies strength parameters under triaxial loading, with the friction angle decreasing from approximately 50° to 40° and the apparent cohesion increasing from approximately 11 MPa to 22 MPa with increasing exposure. The increase in cohesion reflects a confinement-dependent microcrack closure response rather than intrinsic material strengthening, highlighting the importance of stress state in interpreting strength parameters of FT-conditioned rocks.
3. Indirect tensile strength exhibits greater sensitivity to slow FT exposure than compressive behavior, with reductions of approximately 7% observed after short-term conditioning, confirming the dominant role of crack-controlled failure mechanisms under tensile loading. The partial recovery observed at longer durations remains mechanistically unresolved and is identified as a subject for future microstructural investigation.

Overall, the results suggest that FT cycle rate plays an important role in governing stiffness and deformation behavior, while strength and fracture properties respond primarily to cumulative slow FT exposure. This distinction has direct implications for durability assessments in cold-region rock

engineering: cycle count alone is an insufficient proxy for FT damage severity, and thermal cycling rate should be considered alongside total exposure duration.

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