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Influence of Freeze–Thaw Cycles on the Behavior of Fiber-Reinforced Shotcrete

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Abstract

The freeze-thaw (FT) phenomenon substantially influences the mechanical performance and long-term durability of tunnels constructed in cold regions. Repeated cycles of freezing and thawing cause the progressive degradation of the shotcrete lining, leading to reduced stiffness, the development of microcracks, and the expansion of the damaged region at tunnel boundaries. This degradation reduces load-bearing capacity and compromises the structural integrity of underground openings exposed to FT cycles, emphasising the need to understand the impact of freeze-thaw-induced deterioration on tunnel support systems.
In this study, a comprehensive numerical analysis was carried out to evaluate the influence of freeze–thaw (FT) degradation on the performance of fiber-reinforced shotcrete (FRS) tunnel linings. A detailed parametric investigation was conducted to examine the behavior of shotcrete with varying fiber dosages under different in-situ stress conditions. The analysis focused on deformation patterns, axial, bending, and shear force, and the evolution of the damaged zone (radius of plastic zone) around the tunnel under static loading.

The results show that both the thickness and intensity of the damaged zone increased with the number of FT cycles, with the most severe damage occurring near the tunnel periphery. The gradual decrease in stiffness and bonding effectiveness of the shotcrete lining under FT exposure caused increased deformation and the development of a damaged zone. However, increasing the steel fiber dosage effectively reduced the required lining thickness while enhancing ductility and resistance to FT-induced degradation. Overall, the findings highlight the critical role of fiber reinforcement and optimized shotcrete design in maintaining long-term tunnel stability in cold-region environments.

Keywords

Freeze–thaw cycles, Shotcrete, Mechanical degradation, Damaged zone, Fiber-reinforced.

1 Introduction

Tunnels constructed in cold regions are subjected to freezing and thawing, which adversely affect the durability and structural integrity of tunnel linings. Freeze–thaw damage occurs when pore water freezes and expands by about 9%, generating tensile stresses that initiate or widen cracks in the material. During thawing, the melted water infiltrates these cracks, increasing permeability and accelerating crack propagation under repeated FT cycles (Chen et al., 2021). This deterioration in the rock mass and shotcrete lining can lead to increased deformation, altered stress redistribution, and expansion of the plastic zone around the excavation boundary, ultimately affecting tunnel stability. Therefore, understanding these effects is essential for designing durable and resilient tunnel infrastructure in cold-region environments.

Previous studies have reported that unreinforced shotcrete is highly susceptible to freeze–thaw (FT) deterioration, exhibiting pronounced surface scaling, progressive stiffness degradation, and microstructural damage under repeated FT cycling. It also reported that fibre reinforcement is an effective approach to mitigate freeze–thaw (FT) induced deterioration. Various fibre types, including polypropylene (PP) (Wang & Chen, 2019), glass (Lohar, et al., 2025), and basalt fibres (Y. Guo et al., 2024)help control microcrack initiation, reduce permeability, and improve resistance to mass loss, thereby enhancing durability and maintaining matrix integrity under FT conditions. In particular, steel fibres improve crack-bridging capacity, maintain residual strength, and reduce stiffness degradation under freeze–thaw conditions (Han et al., 2025). Consequently, steel fibres are commonly used as the primary reinforcement in shotcrete for tunnel construction. However, limited research has been conducted on the performance of fibre-reinforced shotcrete subjected to repeated FT cycles, particularly under conditions representative of tunnel environments.

These issues are particularly relevant for tunnels constructed in the western Himalayan region. Among these, the Atal Tunnel experiences prolonged sub-zero temperatures and continuous moisture ingress for several months each year, making it an ideal case for investigating long-term freeze–thaw (FT) effects on tunnel infrastructure (Jain & Rao, 2022). Although several laboratory studies have examined the deterioration of concrete under FT cycles, the direct relationship between FT-induced material degradation and the structural response of tunnel linings under actual geological and loading conditions remains insufficiently explored.

In addition to environmental effects, the mechanical response and stability of tunnels are strongly influenced by the in-situ stress conditions of the surrounding rock mass. Earlier studies commonly assumed isotropic stress conditions (K=1); however, field measurements have shown considerable variation in the horizontal-to-vertical stress ratio depending on geological and tectonic settings (Hoek & Brown, 1997). Such variations have been reported to influence the stability of several Himalayan tunnel projects (Shrestha & Panthi, 2015). Tunnel excavation also causes stress redistribution around the opening due to the stress arching mechanism, first analytically described by Kirsch (1898) and later investigated through analytical and numerical studies(Z. Guo et al., 2021). More recent research has examined the mechanical behaviour of tunnels under anisotropic stress conditions and squeezing ground environments (Adhikari et al., 2025; Lohar et al., 2024; Lohar, Kumar, et al., 2025). However, the combined influence of freeze–thaw cycles on tunnel lining materials, particularly considering different fiber dosages in fiber-reinforced shotcrete under varying in-situ stress conditions, remains largely unexplored. Therefore, further research is required to evaluate how FT-induced material degradation interacts with in-situ stress conditions to influence the mechanical performance and long-term stability of tunnel linings.

In this study, a comprehensive numerical analysis was carried out to evaluate the influence of freeze–thaw (FT) degradation on the performance of fiber-reinforced shotcrete (FRS) tunnel linings. A detailed parametric investigation was conducted to examine the behavior of shotcrete with varying fiber dosage under different in-situ stress conditions. The analysis focused on deformation patterns, axial and bending behaviour of tunnel lining, and the evolution of the damaged zone around the tunnel under static loading.

2 Methodology

Detailed numerical modelling was performed by incorporating experimentally obtained material properties of Plain shotcrete (PS) and steel fiber reinforced shotcrete (SFRS) subjected to different FT cycles. The key response parameters, axial force, bending moment, shear force, tunnel displacement, and plastic zone development, were evaluated through a parametric study to assess the influence of FTCs and fibre dosage on lining stability. The tunnel radius was 6.6 m, and geometric symmetry was assumed about the vertical axis (y = 0). Boundary conditions were applied with the top and right boundaries fixed in both directions, the left boundary fixed in the x-direction, and the bottom

boundary fixed in the y-direction. The model was discretized using six-noded triangular elements with mesh refinement near the tunnel boundary. In-situ stresses were applied using field-stress initialization, and staged excavation was simulated in increments of 0.2D following (Carranza-Torres & Diederichs, 2009).

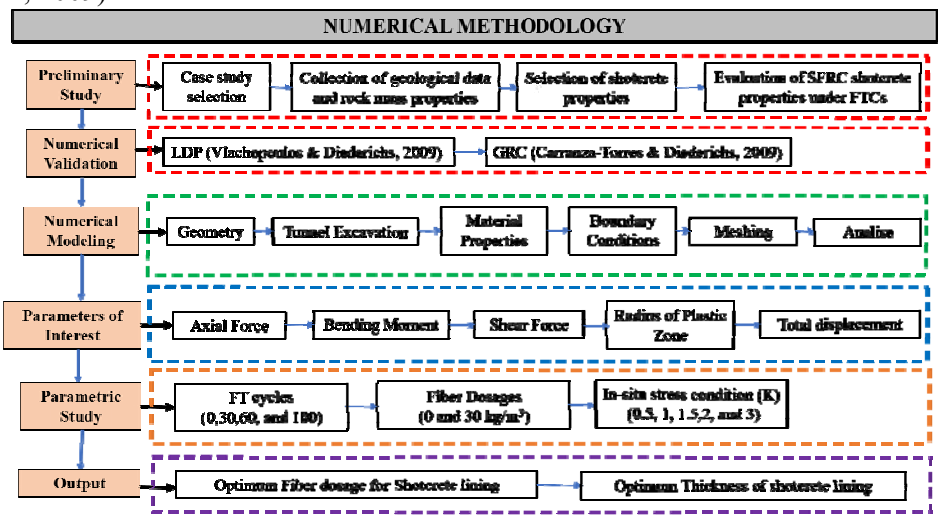


Fig. 1 Numerical methodology adopted in the study.

3 Numerical Validation

The numerically validated model successfully reproduced the previously reported ground reaction curves (GRC) (Fig.2) and longitudinal displacement profiles (LDP) (Fig. 3), confirming the reliability of the numerical framework. The numerical LDP showed close agreement with the analytical solution of (Vlachopoulos & Diederichs, 2009), while the GRC matched well with the analytical formulation of (Carranza-Torres & Fairhurst, 2000), thereby validating the modelling approach before incorporating FT-degraded shotcrete properties.

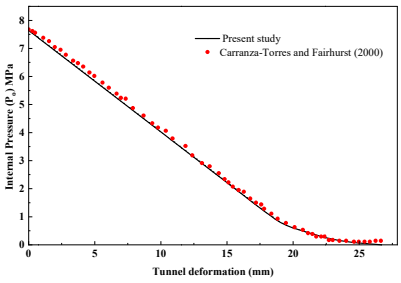


Fig. 2 Numerical Validation of GRC

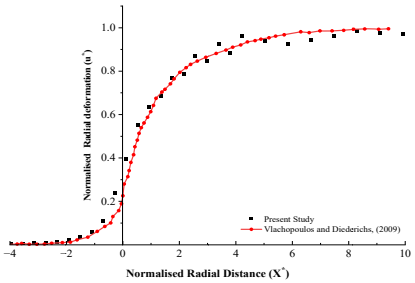


Fig. 3 Numerical validation for LDP

3.1 Material properties for Finite Element analysis

The rock mass properties adopted in the numerical analysis, taken from (Jain, 2019)for chainage 2+011, are summarized in Table 2. The shotcrete material properties corresponding to different freeze–thaw cycles were obtained from the experimental investigations carried out in this study and are presented in Table 1. These material properties are used in the numerical analysis.

Table 1. Mechanical properties of concrete with varying dosage of steel fibre.

Dosage of steel fibres (kg/m^3)	FT	UCS (MPa)	E (GPa)	Tensile Strength (MPa)	Poisson's ratio (μ)
0	0	40.54	36.581	7.102	0.24
	30	36.43	35.557	6.087	0.24
	60	28	24.794	3.872	0.24
	100	21.54	11.596	1.582	0.24
30	0	66.93	57.118	14.287	0.284
	30	60.95	55.15	13.144	0.284
	60	54.84	40.02	12.001	0.284
	100	51.79	38.863	10.715	0.284

Table 2. Rock mass parameters at the Atal tunnel (Jain, 2019).

CH	γ (kN/m^3)	E_i (MPa)	E_{rm} (MPa)	GSI	ν	σ_{ci} (MPa)	H (m)	m_b	m_i	s	a
2 + 011	26.88	43.28	2990.7	27.4	0.3	83.6	284	1.496	20	0.0003	0.527

4 Results and Discussions

4.1 Effect of Fiber Dosage

The influence of fiber dosage on the structural response of the shotcrete lining was evaluated by comparing 0 kg/m³ and 30 kg/m³ steel fiber contents under different in-situ stress ratios (K). At FT = 0, the fiber-reinforced lining shows higher structural capacity. After 100 FT cycles, the plain shotcrete lining exhibits significant deterioration. For instance, at *K=0.5,* the axial force in PS decreases by 28.6% (1276.5 kN to 911.3 kN), while the fiber-reinforced lining shows only a 7.3% reduction for 0 to 100 FT cycles of shotcrete. A similar trend is observed at *K=3*, where PCC shows reductions of about 19% in axial force and 64.6% in bending moment, whereas the fiber-reinforced lining shows smaller reductions of about 3.2% and 26.1%. Shear force also decreases more significantly in PS, while the fiber-reinforced lining exhibits comparatively smaller changes. Additionally, FT cycles slightly increase tunnel displacement and the plastic zone radius, particularly for plain shotcrete. Finally, the results indicate that the inclusion of 30 kg/m³ steel fibers effectively mitigates FT-induced deterioration and improves the structural performance and durability of tunnel linings.

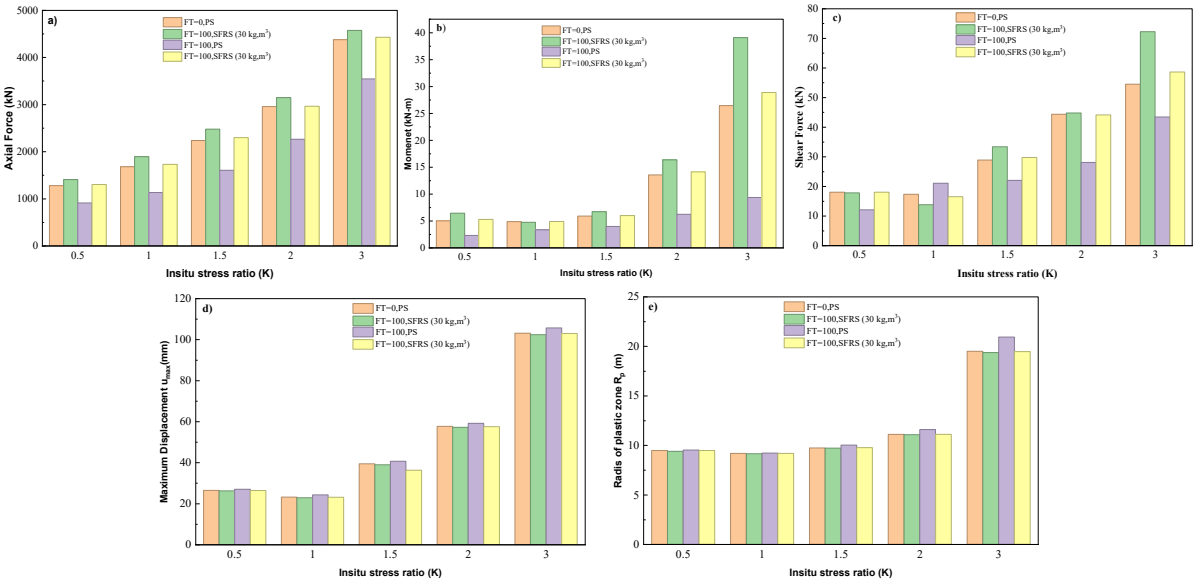


Fig. 4 Variation of shotcrete lining response and tunnel deformation with in-situ stress ratio (K) at CH 2+011: **(a)** axial force, **(b)** bending moment, **(c)** shear force, (**d)** maximum tunnel displacement, and **(e)** radius of the plastic zone.

4.2 Effect of Freeze–Thaw Cycles

The influence of freeze–thaw (FT) cycles on shotcrete lining response and tunnel deformation at CH 2+011 was evaluated for *K*=1 and *K*=3. Increasing FT cycles progressively degrade the structural response of PS shotcrete (0 kg/m³ fiber), while fiber-reinforced shotcrete (30 kg/m³) shows improved resistance. For *K* = 1, PS shows reductions of about 32% in axial force and 31% in bending moment, whereas the fiber-reinforced lining shows only minor reductions. At *K*=3, the degradation becomes more pronounced, with PS exhibiting about 19% reduction in axial force and 65% reduction in bending moment, while the fiber-reinforced lining shows smaller decreases. Shear force, tunnel displacement, and plastic zone radius increase slightly with FT cycles due to stiffness degradation.

Table 3. Shotcrete lining response and tunnel deformation at CH 2+011 under different freeze–thaw cycles.

Stress ratio (K)	FT Cycles	Axial Max (0kg)	Axial Max (30kg)	BM Max (0kg)	BM Max (30kg)	SF Max (0kg)	SF Max (30kg)	u_{max} (0kg)	u_{max} (30kg)	R_p (0kg)	R_p (30kg)
1	0	1677.3	1892.6	4.88	4.74	17.33	13.79	23.186	22.828	9.195	9.156
	30	1664.3	1879	4.87	4.79	17.47	14.13	23.21	22.851	9.202	9.167
	60	1505	1741.6	4.54	4.90	18.82	16.34	23.53	23.076	9.212	9.175
	100	1133.6	1728.2	3.36	4.90	21.07	16.52	24.299	23.099	9.218	9.182
3	0	4575	26.46	39.10	54.50	72.23	103.164	102.454	19.5	19.377	4379
	30	4565	25.77	38.07	53.19	70.69	103.21	102.5	19.443	19.394	4365.8
	60	4448.5	19.62	29.55	49.23	58.75	103.87	102.944	20.884	19.424	4175.6
	100	4428	9.36	28.90	43.44	58.64	105.75	102.984	20.95	19.484	3544.9

4.3 Effect of In-Situ Stress Ratio (K) on Tunnel Displacement

The variation of maximum displacement for FT = 100 under different in-situ stress ratios (*K*) is shown in Fig. 5. The displacement starts at 27.01 mm (0 kg/m³) and 26.40 mm (30 kg/m³) at $K = 0.5$, decreases slightly at $K = 1$, and then increases with increasing stress ratio. The maximum displacement occurs at $K = 3$, reaching 105.75 mm for plain shotcrete and 102.98 mm for fiber-reinforced shotcrete. The fiber-reinforced lining exhibits slightly lower displacement compared to the plain lining.

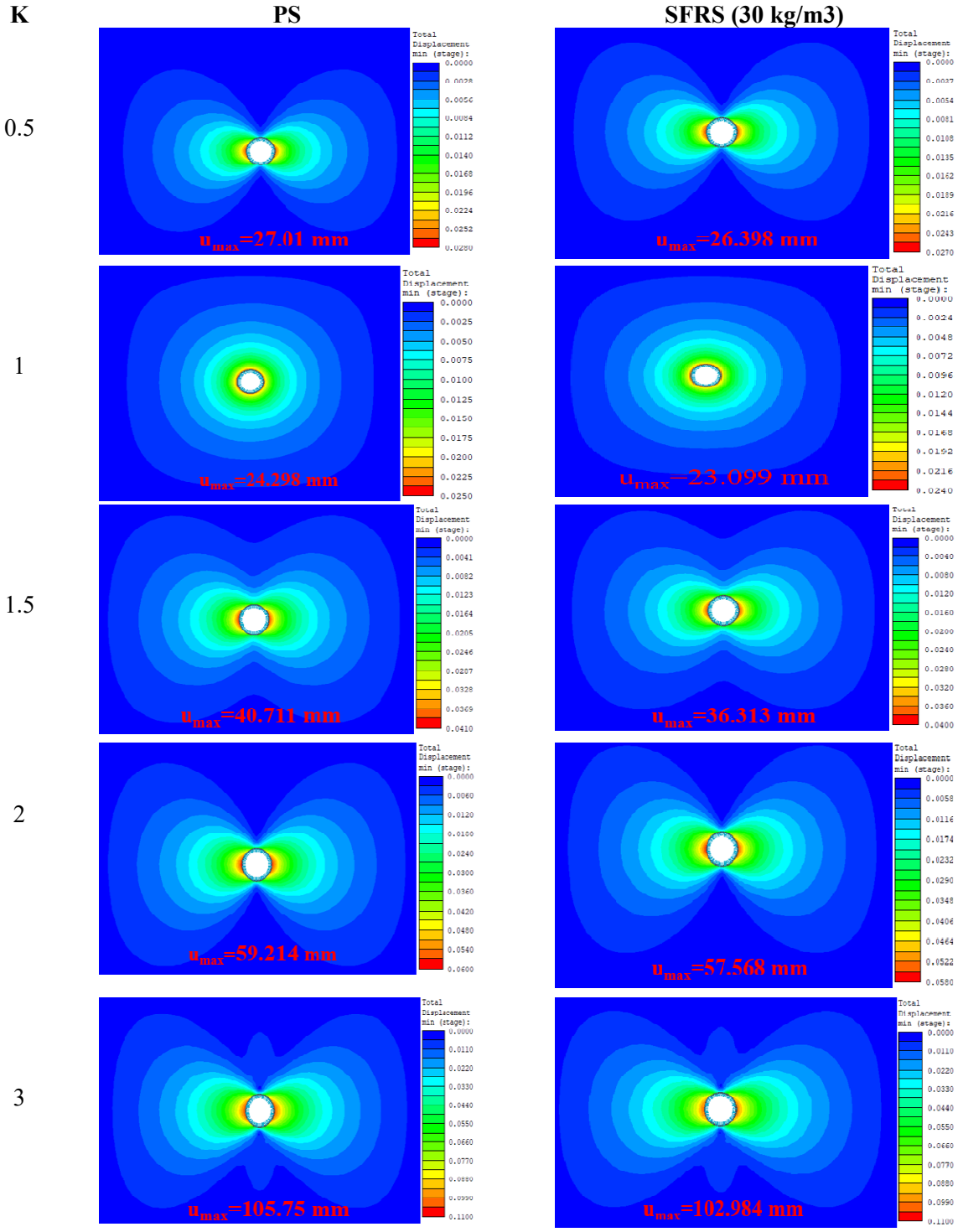


Fig. 5 Total tunnel displacement contours for different FT cycles comparing PS and SFRS (30 kg/m³).

5 Conclusions

Based on the numerical analysis of tunnel lining response under different freeze–thaw (FT) cycles, fiber dosages, and in-situ stress ratios (*K*), the following conclusions can be drawn:

- Freeze–thaw (FT) cycles progressively degrade the structural response of plain shotcrete (PS), leading to reductions in axial force, bending moment, and stiffness.
- The deterioration becomes more pronounced at higher in-situ stress ratios, particularly at K=3, where PS shows significant reductions in structural capacity.
- Steel fiber reinforcement (30 kg/m³) significantly improves resistance to FT-induced damage, resulting in smaller reductions in axial and bending capacities compared to plain shotcrete.
- Fiber-reinforced shotcrete also exhibits slightly lower tunnel displacement and plastic zone expansion, indicating improved stiffness and crack resistance.
- Overall, the incorporation of steel fibers enhances the durability and structural performance of tunnel linings under freeze–thaw conditions and varying in-situ stress environments.

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