# Freeze–Thaw Resistance of Fly Ash–Steel Slag Recycled Concrete for Cold-Region Applications: Experimental Study Based on Ganzi Prefecture Conditions

*SiYuan Li[1], Chaiporn Supahitanukool[1], Phanupong Samol[1*] and Winai Ouypornprasert[2]*
*Faculty of Engineering and Technology, Pathumtani University[1]*
*Faculty of Engineering and Technology, Pathumtani University[1*]*
*College of Engineering, Rangsit University[2]*
*Corresponding author's e-mail: phanupong.s@ptu.ac.th*

## Abstract

Concrete in alpine cold regions is highly susceptible to freeze–thaw damage and durability deterioration. Fly ash (FA) and steel slag (SS) offer pozzolanic and pore-filling benefits, yet their optimal composite proportion for extreme freeze–thaw environments remains insufficiently defined.This study evaluated C30 recycled concrete with nine FA–SS proportions (replacement: 20–40%; FA:SS: 1:1, 2:1, 3:1) through compressive strength, mass loss, RDEM, and rapid freeze–thaw cycling tests. FA–SS incorporation significantly improved freeze–thaw durability at moderate dosages, while excessive replacement reduced strength and compactness. A 30% replacement rate with FA:SS ratio of 2:1 demonstrated optimal mechanical–durability balance, providing practical mix design guidance for green recycled concrete in alpine cold regions.

**Keywords**: fly ash–steel slag recycled concrete; freeze–thaw resistance; alpine cold regions; mix proportion optimization; durability; green concrete

## Introduction

Concrete infrastructure in alpine cold regions such as Ganzi Prefecture suffers accelerated durability deterioration from extreme temperatures and frequent freeze–thaw cycling (Qin et al., 2025; Tang, 2019). Fly ash (FA) and steel slag (SS) effectively modify concrete microstructure through pore-filling, pozzolanic activity, and latent hydraulic reactivity (Chen et al., 2022; Ye et al., 2018), yet their optimal composite proportion for extreme freeze–thaw environments remains insufficiently defined (Wang et al., 2017; Zhou et al., 2024).This study evaluates FA–SS recycled C30 concrete for Ganzi Prefecture infrastructure, assessing: (1) compressive strength under standard curing and freeze–thaw cycling; (2) frost resistance via mass loss, RDEM, and strength loss rate; and (3) optimal FA–SS replacement level for balanced mechanical and durability performance.

## Materials and Methods

- **Materials and Mix Design** C30 concrete was prepared using Ordinary Portland Cement (P·O 42.5), Class I fly ash (FA) sourced from Ganzi Prefecture Xuanhe Heating Co., Ltd., thermally treated ground steel slag (SS) powder from Kangding County Kangli Co., Ltd., crushed limestone (5–25 mm), local river sand (FM ≈ 2.8), potable water, polycarboxylate superplasticizer (water reduction rate: 28.5%), and SJ-2 air-entraining agent. The base mix comprised cement 440, fine aggregate 682, coarse aggregate 1,288, water 198, superplasticizer 4.4, and air-entraining agent 0.088 kg/m³, with a fixed water–binder ratio of 0.45. Nine experimental groups were designed by varying total cement replacement rate (20%, 30%, 40%) and FA:SS ratio (1:1, 2:1, 3:1), with a plain concrete control (CK, 0% replacement) as baseline. All other mix components remained constant across groups.
- **Specimen Preparation and Testing A** controlled laboratory experimental program was conducted including specimen preparation, mechanical testing, and rapid freeze–thaw cycle durability assessment. All procedures complied with GB/T 50081-2019 and GB/T 50082-2009 to ensure reliability and reproducibility.
- **Experimental Program**
  - Specimen PreparationCube specimens (100 mm) were cast for compressive strength tests, and prisms (100 mm × 100 mm × 400 mm) for freeze–thaw and dynamic elastic modulus measurements, using a 50 L forced mixer to ensure uniform dispersion. Three parallel specimens were prepared per test point. All specimens were demolded after 24 hours and cured at 20 ± 2 °C and RH ≥ 95% for 28 days.
  - Testing ProgramCompressive strength was measured per GB/T 50081-2019 using a 2000 kN hydraulic testing machine after 28-day curing and after 0, 100, and 200 freeze–thaw cycles. Strength loss rate was calculated as $Rc = (fc0 - fcn) / fc0 \times 100\%$. Relative dynamic elastic modulus (RDEM) was determined from transverse resonance frequency per GB/T 50082-2009, calculated as $RDEM = (fn / f0)^2 \times 100\%$, reflecting internal structural integrity during cycling. Mass loss rate was evaluated from saturated surface-dry mass measurements as $Wn = (G0 - Gn) / G0 \times 100\%$.
  - Durability TestingSpecimens underwent 200 rapid freeze–thaw cycles alternating between −15 ± 2 °C (3 hours freezing) and 5 ± 2 °C (1 hour thawing), reproducing the environmental stress conditions of Ganzi Prefecture. Compressive strength, RDEM, mass loss, and surface deterioration were evaluated at 0, 100, and 200 cycles.
- **Data Analysis** Results were expressed as mean values of at least three replicates with standard deviations. Mechanical strength, mass loss, and RDEM were compared across mix proportions as percentage changes relative to the control. Strength degradation and structural integrity after freeze–thaw cycling were analyzed to assess long-term frost durability. All procedures complied with GB/T 50081-2019 and GB/T 50082-2009.

## Result

1) **Workability** Increasing FA–SS replacement rate produced a two-stage effect on fresh concrete workability. At replacement rates ≤30%, the spherical morphology of fly ash provided a lubricating effect, maintaining acceptable slump for cast-in-place construction. At 40% replacement, workability decreased significantly regardless of FA:SS ratio, attributed to the high specific surface area of steel slag and increased water demand of the composite admixture.
2) **Compressive StrengthFA–SS** composite admixtures exhibited a dosage-dependent effect on 28-day compressive strength (Fig. 1). At 30% replacement with FA:SS ratio of 2:1, strength increased by 6–8% over the control, representing optimal performance. At 20% replacement, all FA:SS ratios remained within ±5% of the control, satisfying C30 requirements. At 40% replacement, strength declined by 7–14% due to reduced clinker content and insufficient early hydration. The improvement at moderate dosages is attributed to synergistic micro-aggregate filling and secondary pozzolanic reaction enhancing the interfacial transition zone.Under freeze–thaw cycling, FA–SS concrete exhibited significantly lower strength deterioration. After 200 cycles, the control group lost 31.2% of compressive strength, whereas the optimal 30% replacement group (FA:SS = 2:1) lost only 12.7%.

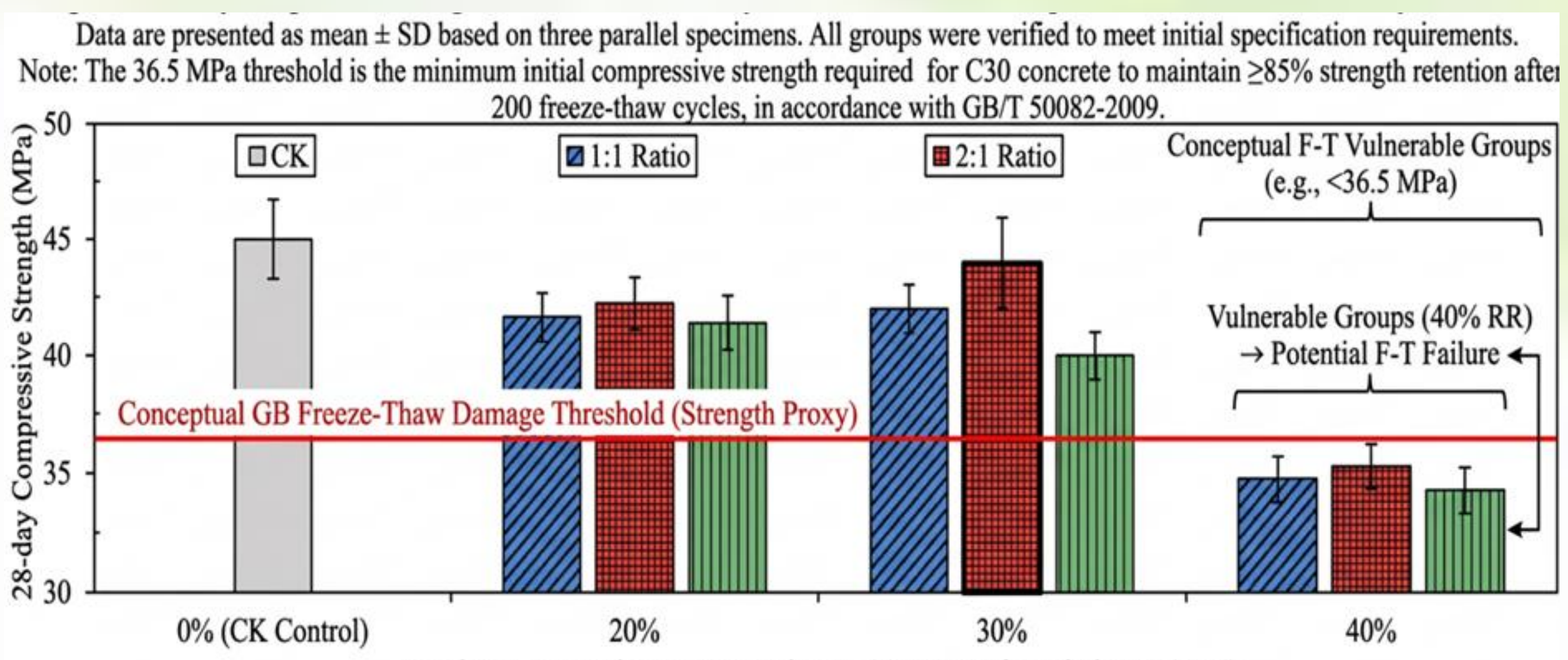
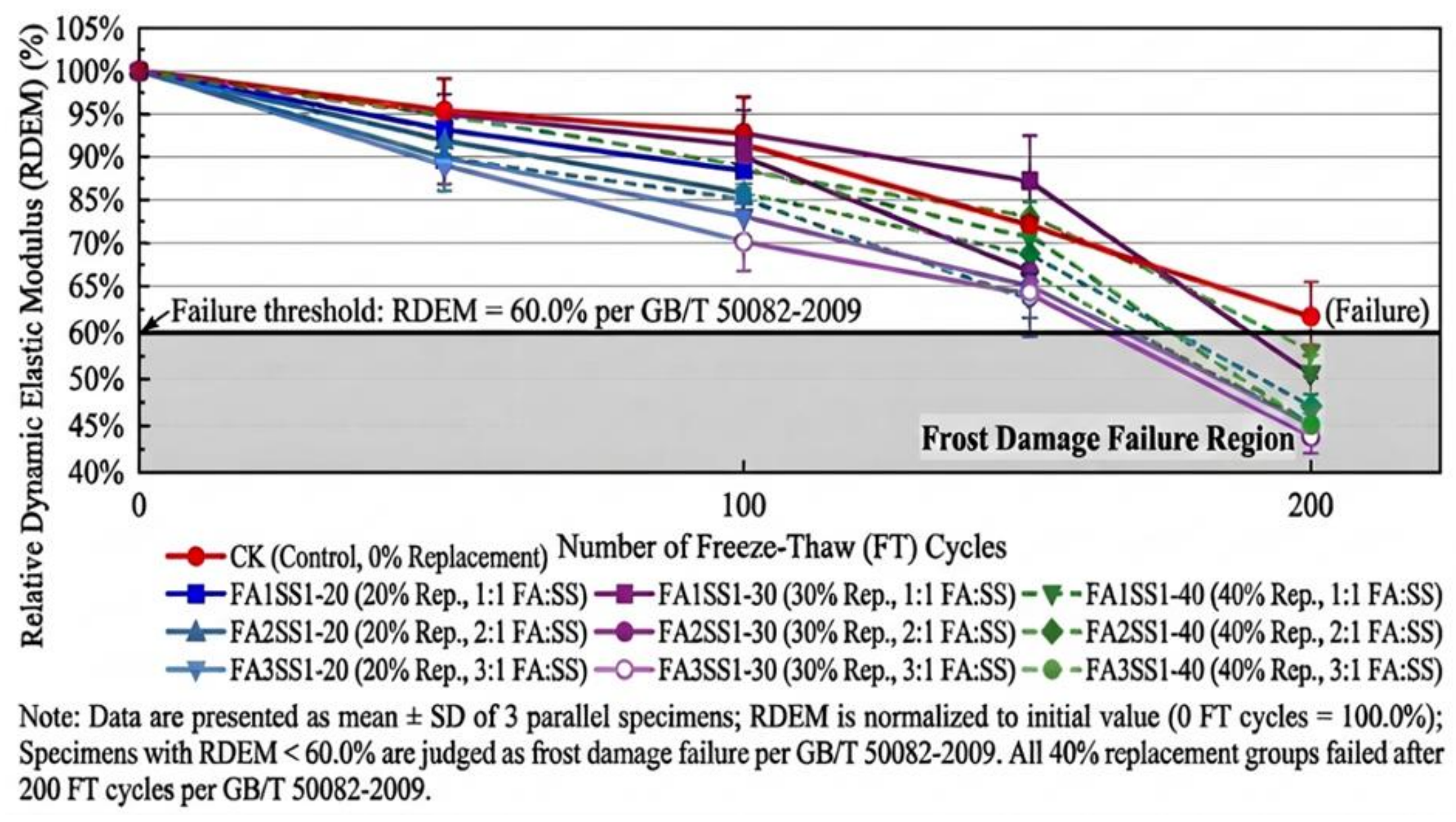

Data are presented as mean ± SD based on three parallel specimens. All groups were verified to meet initial specification requirements.
Note: The 36.5 MPa threshold is the minimum initial compressive strength required for C30 concrete to maintain ≥85% strength retention after 200 freeze-thaw cycles, in accordance with GB/T 50082-2009.

**Figure 1.** 28-day compressive strength of FA-SS blended recycled concrete, with conceptual freeze-thaw vulnerability threshold.

3) **Relative Dynamic Elastic Modulus (RDEM)RDEM** served as a non-destructive indicator of internal structural integrity during freeze–thaw cycling (Fig. 7). After 200 cycles, the control group's RDEM dropped to 58.7%, falling below the 60% frost damage threshold per GB/T 50082-2009. In contrast, all FA–SS groups at 20% and 30% replacement maintained RDEM above 60%. The optimal 30% replacement group (FA:SS = 2:1) retained 86.2% of initial RDEM (+27.5% over control), confirming effective mitigation of internal frost-heaving stress and microcrack propagation.



Note: Data are presented as mean ± SD of 3 parallel specimens; RDEM is normalized to initial value (0 FT cycles = 100.0%); Specimens with RDEM < 60.0% are judged as frost damage failure per GB/T 50082-2009. All 40% replacement groups failed after 200 FT cycles per GB/T 50082-2009.

**Figure 2.** Relative dynamic elastic modulus (RDEM) of specimens after different freeze-thaw (FT) cycles.

4) **Mass Loss Characteristics** Mass loss reflected surface deterioration from mortar spalling under freeze–thaw stress (Fig. 8). After 200 cycles, the control group exhibited 5.12% mass loss, exceeding the 5% failure threshold per GB/T 50082-2009, with visible aggregate exposure. The optimal 30% replacement group (FA:SS = 2:1) achieved the lowest mass loss of 1.87% (−63.5% versus control). Mass loss increased significantly at replacement rates exceeding 30%, attributed to reduced matrix continuity and increased interfacial defects.

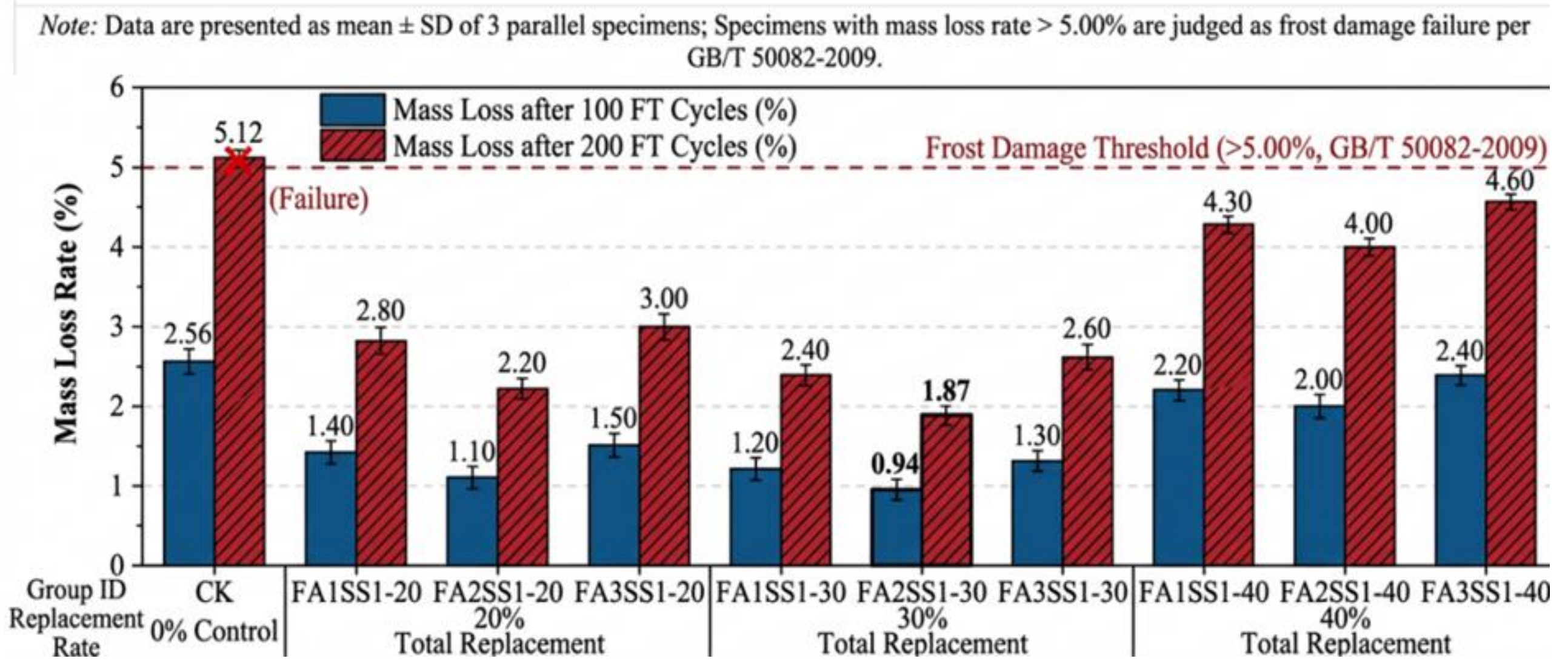

*Note:* Data are presented as mean ± SD of 3 parallel specimens; Specimens with mass loss rate > 5.00% are judged as frost damage failure per GB/T 50082-2009.

**Figure 3** Mass loss rate of specimens after different freeze-thaw (FT) cycles.

5) **Frost Resistance Grade** Per GB/T 50082-2009, the control group achieved only F100 frost resistance, failing to reach F200. All FA–SS groups at 20% and 30% replacement attained F200, meeting durability requirements for Ganzi Prefecture infrastructure. The 30% replacement group (FA:SS = 2:1) demonstrated superior performance within F200, retaining 86.2% RDEM with only 1.87% mass loss. Groups at 40% replacement achieved only F150, with RDEM dropping below 60% between 150 and 200 cycles.
6) **Overall Performance Evaluation** Across all indicators, a total cement replacement rate of 30% with FA:SS ratio of 2:1 provided the most balanced performance: +6–8% compressive strength, −63.5% mass loss, +27.5% RDEM retention after 200 cycles, with acceptable workability for cast-in-place construction.

## Conclusions

FA–SS composite admixtures significantly enhanced freeze–thaw resistance and mechanical performance of concrete under simulated alpine cold conditions. A total cement replacement rate of 30% with FA:SS ratio of 2:1 provided the optimal balance of compressive strength, frost resistance, structural integrity, and workability. Replacement rates exceeding 40% led to reduced strength, inferior frost resistance, and poor workability. These findings provide practical mix design guidance for durable infrastructure in alpine cold regions. This study was limited to laboratory-scale specimens and controlled freeze–thaw cycling; long-term field validation incorporating wind erosion, UV radiation, and traffic loads is recommended.

## Recommendations and Future Work

A total cement replacement rate of 30% with FA:SS ratio of 2:1 is recommended for infrastructure in Ganzi Prefecture and similar alpine regions, achieving balanced frost resistance, mechanical performance, and local industrial by-product utilization. Future research should focus on long-term field validation, full-scale structural testing, and mix optimization (e.g., water–binder ratio, compound admixture systems) to confirm practical applicability under real engineering conditions.

## References

Chen, H., Yu, R., Shui, Z., & Wang, X. (2022). Performance evaluation of steel slag-fly ash composite concrete under freeze-thaw cycles. Construction and Building Materials, 346, 128452. https://doi.org/10.1016/j.conbuildmat.2022.128452

Qin, W., et al. (2025). Influence of low-temperature curing on strength and frost resistance of cold-resistant concrete in alpine regions. Construction Technology, 54(2), 89–93.

Shi, C., Jiménez, A. F., & Palomo, A. (2018). New cements for the 21st century: The pursuit of low-$CO_2$ cementitious materials. Cement and Concrete Research, 114, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

Tang, S. (2019). Frost damage mechanism of concrete in cold regions: A review. Journal of Building Materials, 22(4), 545–556.

Wang, C., et al. (2017). Influence of fly ash content on mechanical properties and frost resistance of recycled concrete. Bulletin of the Chinese Ceramic Society, 36(7), 2245–2251.

Yang, Y., et al. (2024). Mechanical properties degradation of concrete under long-term freeze-thaw cycles. Journal of Materials in Civil Engineering, 36(5), 04024056. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004789

Ye, H., et al. (2018). Synergistic effect of fly ash and steel slag on frost resistance of concrete. Concrete, 12, 78–82.

Zhang, P., Kang, L., & Hou, D. (2022). Durability of fiber-reinforced cementitious materials under temperature and humidity cycling. Cement and Concrete Composites, 132, 104653. https://doi.org/10.1016/j.cemconcomp.2022.104653

Zhou, Y., Li, X., & Xu, S. (2024). Optimization of mineral admixture content for frost resistance of concrete in alpine regions. Construction and Building Materials, 412, 134567. https://doi.org/10.1016/j.conbuildmat.2023.134567