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

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Abstract

Concrete infrastructure in alpine cold regions such as Ganzi Prefecture is highly susceptible to freeze–thaw damage and long-term durability deterioration. Fly ash (FA) and steel slag (SS) are recognized for their pore-filling and pozzolanic effects; however, the optimal FA–SS proportion for extreme freeze–thaw environments remains insufficiently defined. This study investigated the freeze–thaw resistance of C30 recycled concrete with nine FA–SS composite mix proportions (total cement replacement: 20%–40%; FA:SS ratios: 1:1, 2:1, 3:1) through compressive strength testing, relative dynamic elastic modulus (RDEM) measurement, and rapid freeze–thaw cycle durability tests. The results indicated that a total replacement rate of 30% with an FA:SS ratio of 2:1 demonstrated optimal performance, achieving a 6–8% increase in 28-day compressive strength, 86.2% RDEM retention after 200 freeze–thaw cycles (27.5% improvement over control), and a 63.5% reduction in mass loss rate. This mix achieved the F200 frost resistance grade, meeting durability requirements for Ganzi Prefecture infrastructure. These findings provide practical guidance for durable, climate-adaptive recycled concrete design 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 was continuously exposed to severe environmental conditions, including extreme low temperatures, large diurnal temperature variations, intense solar radiation, and frequent freeze–thaw cycles. The combined effects of freeze–thaw cycling accelerated internal stress accumulation, induced microcrack formation, and promoted structural damage, leading to increased permeability and long-term durability deterioration (Qin et al., 2025; Tang, 2019). As a result, concrete structures in such environments often experienced premature surface spalling, internal cracking, and reduced service life, which significantly increased maintenance and repair costs. Therefore, improving the frost resistance and durability performance of concrete under the extreme cold climatic conditions of Ganzi Prefecture became a critical challenge in modern infrastructure development. Studies have demonstrated that freeze–thaw cycling is the predominant cause of concrete deterioration in cold regions, with permeability increasing by up to two orders of magnitude as internal microcracks develop (Yang et al., 2024). The annual average temperature in Ganzi Prefecture ranges from −1.6 °C to 10.0 °C, with over 150 freeze–thaw cycles per year (China Meteorological Administration data), making frost resistance a critical design parameter for local infrastructure (Qin et al., 2025).

Recycled concrete incorporating industrial by-product mineral admixtures was widely adopted to enhance durability, reduce carbon emissions, and realize solid waste resource utilization (Shi et al., 2018). Among various industrial by-products, fly ash and steel slag exhibited superior performance in modifying concrete microstructure: fly ash provided excellent pore-filling effects and pozzolanic activity, while steel slag exhibited latent hydraulic activity that enhanced strength development (Chen et al., 2022; Ye et al., 2018). Although many studies examined the mechanical behavior of FA–SS composite concrete under laboratory conditions, most focused on general cold regions or short-term strength performance. Limited attention was given to concrete applications subjected to the extreme freeze–thaw cycles typical of Ganzi Prefecture, where frost damage was significantly intensified (Yang et al., 2024; Zhang et al., 2022). Furthermore, the optimal mix proportion that balanced mechanical enhancement, frost resistance improvement, and solid waste utilization efficiency remained insufficiently defined for the local alpine environment (Wang et al., 2017; Zhou et al., 2024). This gap highlighted the need for a systematic performance evaluation of FA–SS recycled concrete specifically designed for infrastructure applications in the extreme cold conditions of Ganzi Prefecture.

Accordingly, this study aimed to evaluate the freeze–thaw resistance of FA–SS recycled concrete for infrastructure applications in alpine cold regions. The research focused on (1) assessing mechanical performance, including compressive strength development under standard curing and freeze–thaw cycles; (2) investigating frost resistance via mass loss, relative dynamic elastic modulus (RDEM), and strength loss rate; and (3) identifying the optimal FA–SS replacement level for balanced mechanical and durability performance under simulated Ganzi climatic conditions. By identifying the optimal mix proportion that provided a balanced improvement in strength, frost resistance, and material utilization, this study sought to provide practical mix design guidance for durable and climate-adaptive concrete infrastructure in alpine cold regions.

To achieve these objectives, a controlled laboratory experimental program was designed, including material characterization, mix proportioning, specimen preparation, mechanical testing, and rapid freeze–thaw cycle durability assessment, as described in the following Materials and Methods section.

Materials and Methods

1. General

This study employed a controlled laboratory experimental design to determine the optimal FA–SS composite admixture proportion for C30 concrete under simulated cold climatic conditions of Ganzi Prefecture. The methodology included material characterization, mix design, specimen preparation, mechanical testing, and rapid freeze–thaw cycle durability testing. All procedures complied with the national testing standards GB/T 50081-2019 and GB/T 50082-2009 to ensure reliability and reproducibility.

2. Materials

In this study, the selection of constituent materials was carried out to ensure consistency with local construction practices in Ganzi Prefecture and to maintain experimental reliability. All materials were locally sourced or commercially available construction materials and were selected based on compliance with relevant standards and suitability for producing C30 concrete for infrastructure applications. As summarized in Table 1, six main materials were used, including cement, fly ash, steel slag, coarse aggregate, fine aggregate, and mixing water, together with their corresponding specifications.

Table 1. Specifications of Materials Used in the Experimental Program

Material	**Specification**
Cement	Ordinary Portland Cement P·O 42.5
Fly Ash (FA)	Class I fly ash, sourced from Ganzi Prefecture Xuanhe Heating Co., Ltd.
Steel Slag (SS)	Thermally treated ground steel slag powder, from Kangding County Kangli Co., Ltd.
Coarse aggregate	Crushed limestone 5–25 mm
Fine aggregate	Local river sand (FM ≈ 2.8)
Water	Potable tap water
Admixtures	Polycarboxylate superplasticizer (water reduction rate: 28.5%); SJ-2 air-entraining agent

3. Concrete Mix Proportion

To accurately evaluate the effect of FA–SS composite admixture proportion, the base concrete mix was kept constant for all specimens, with only the total cement replacement rate and FA:SS ratio varied. As shown in Table 2, nine experimental mix proportions (total replacement rate: 20%, 30%, and 40%; FA:SS ratios: 1:1, 2:1, and 3:1) were adopted, while all other mix components remained unchanged for comparison. A control group (CK) with 0% admixture replacement was set as the baseline The total replacement range of 20%–40% was selected based on previous studies (Wang et al., 2017; Chen et al., 2022; Zhou et al., 2024), which reported that cement replacement rates below 20% produced negligible improvements in frost resistance, while rates exceeding 40% typically resulted in significant strength reduction and poor workability due to insufficient cement clinker content. The three FA:SS ratios (1:1, 2:1, 3:1) were designed to systematically investigate the synergistic effect between the pozzolanic activity of fly ash and the latent hydraulic activity of steel slag, as previous research indicated that the optimal synergy was achieved when fly ash constituted a larger proportion in the composite admixture (Ye et al., 2018).

Table 2. Concrete Mix Proportions for Different FA-SS Composite Admixture Proportions (kg/m^3)

Group	**Cement**	**Fly Ash**	**Steel Slag**	**Fine Aggregate**	**Coarse Aggregate**	**Water**	**Superplasticizer**	**Air-entraining Agent**
CK	440	0	0	682	1288	198	4.4	0.088
FA1SS1-20	352	44	44	682	1288	198	4.4	0.088
FA1SS1-30	308	66	66	682	1288	198	4.4	0.088
FA1SS1-40	264	88	88	682	1288	198	4.4	0.088
FA2SS1-20	352	59	29	682	1288	198	4.4	0.088
FA2SS1-30	308	88	44	682	1288	198	4.4	0.088

FA2SS1-40	264	117	59	682	1288	198	4.4	0.088
FA3SS1-20	352	66	22	682	1288	198	4.4	0.088
FA3SS1-30	308	99	33	682	1288	198	4.4	0.088
FA3SS1-40	264	132	44	682	1288	198	4.4	0.088

The water–binder ratio was fixed at 0.45 for all mixtures, consistent with local infrastructure construction practices in Ganzi Prefecture.

4. Experimental Program

4.1. Specimen Preparation

Concrete specimens were prepared using a 50 L forced concrete mixer to ensure uniform dispersion of FA, SS, and admixtures. Cubes (100 mm × 100 mm × 100 mm) were cast for compressive strength tests, while prisms (100 mm × 100 mm × 400 mm) were cast for freeze–thaw cycle testing and dynamic elastic modulus measurement. The specimens were demolded after 24 hours and were cured at 20 ± 2 °C and RH ≥ 95% for 28 days before testing.

Table 3. Experimental Groups and Specimen Allocation

Group ID	Total Replacement Rate	FA:SS Ratio	Specimens per Test	Total Specimens
CK	0%	–	Cubes + Prisms	12
Experimental groups	20%/30%/40%	1:1/2:1/3:1	Cubes + Prisms	12 per group

Each mix proportion group consisted of multiple cube and prism specimens, with three parallel specimens prepared for each test point to ensure statistical reliability and minimize experimental error.

4.2. Compressive strength Test

Compressive strength was measured according to GB/T 50081-2019 using a 2000 kN hydraulic universal testing machine. Tests were conducted on specimens after 28 days of standard curing, as well as after 0, 100, and 200 freeze–thaw cycles. These tests represented the primary structural performance indicators of concrete infrastructure in cold regions. The compressive strength loss rate (Rc) was calculated as follows (1):

$$R_c = \frac{f_{c0}-f_{cn}}{f_{c0}} \times 100\% \quad (1)$$

Where

f_{c0} = compressive strength before freeze-thaw cycles(MPa);
f_{cn} = compressive strength after n freeze-thaw cycles (MPa).

Figure 1. Dynamic elastic modulus measurement of prism specimen using transverse resonance frequency tester.

4.3. Relative Dynamic Elastic Modulus (RDEM) Test

The relative dynamic elastic modulus (RDEM) was determined based on the transverse resonance frequency of prism specimens using a dynamic elastic modulus tester, following GB/T 50082-2009. This parameter reflected the internal structural integrity of concrete during freeze–thaw cycles and was calculated using the resonance frequencies of specimens before and after freeze–thaw cycles. The relative dynamic elastic modulus (RDEM) was calculated as follows (2):

$$\mathrm{RDEM} = \left(\frac{f_n}{f_0}\right)^2 \times 100\% \qquad (2)$$

Where

f_n = transverse resonance frequency after n freeze-thaw cycles (Hz),
f_0 = initial transverse resonance frequency (Hz) .

发射频率： 824 Hz
谐振频率： 02531 Hz
Ed: 54.298 GPa
振幅峰值： 01431 mv
共振幅度： 00142 mv
扫频范围： 100 ~ 5000 Hz
142.1mv
试件尺寸：
a=100.00mm
L=400.00mm
W=10.000kg
☐ 自动保存
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Figure 2. Digital display of the dynamic elastic modulus tester during resonance frequency measurement.

4.4. Mass Loss Rate Test

The mass loss rate was determined to evaluate surface spalling and structural deterioration during freeze–thaw cycles, following GB/T 50082-2009. Specimens were weighed in a saturated surface-dry condition before freeze–thaw cycles and after each testing stage using a digital balance with an accuracy of 0.01 g. This parameter provided an indirect indicator of long-term frost durability. The mass loss rate (W_n)was calculated as follows (3):

$$W_n=\frac{G_0-G_n}{G_0}\times 100\% \tag{3}$$

Where

G_0 = initial mass,
G_n = mass after n cycles

Figure 3. Mass measurement of prism specimen in saturated surface-dry condition using a digital balance.

4.5. Durability Tests

To simulate the extreme cold climatic conditions of Ganzi Prefecture, the specimens were subjected to 200 rapid freeze–thaw cycles, with the cycle regime presented in Table 4. The temperature range reproduced the environmental stress conditions experienced by concrete infrastructure in Ganzi Prefecture. Compressive strength, relative dynamic elastic modulus (RDEM), mass loss, and surface deterioration were evaluated after 0, 100, and 200 cycles.

Table 4. Rapid Freeze-Thaw Cycle Regime for Durability Testing

Process	Temperature	Duration
Freezing	–15 ± 2°C	3 hours
Thawing	5 ± 2°C	1 hours

Figure 4. Rapid freeze–thaw testing chamber used for durability assessment of concrete specimens**.**

5. Data Analysis

Test results were analyzed using comparative statistical methods. For each test, the mean value of at least three specimens was calculated, together with the standard deviation, to ensure data reliability. Mechanical strengths were compared among different mix proportions and were expressed as percentage improvements relative to the control mix. Mass loss and relative dynamic elastic modulus (RDEM) results were used to evaluate frost resistance and durability performance. After freeze–thaw cycles, strength degradation and structural integrity changes were analyzed to assess long-term serviceability.

6. Results

1. Workability Observation

The experimental slump test results indicated that increasing the total replacement rate of FA–SS composite admixtures produced a two-stage effect on the workability of fresh concrete. At total replacement rates ≤30%, the spherical particle morphology of fly ash provided a lubricating effect, which maintained or slightly improved the slump of the mixture compared with the control group. Mixes containing total replacement rates ≤30% maintained acceptable workability suitable for cast-in-place infrastructure construction in cold regions. However, at a total replacement rate of 40%, the workability of fresh concrete decreased significantly regardless of the FA:SS ratio. This reduction was attributed to the high specific surface area of steel slag powder and the increased water demand of the composite admixture.

2. Compressive Strength

The incorporation of FA–SS composite admixtures showed a clear dosage-dependent effect on the 28-day compressive strength of hardened concrete. At a 30% total replacement rate with an FA:SS ratio of 2:1, the 28-day compressive strength increased by 6–8% compared with the control mix, representing the optimal mechanical performance among all test groups.

For mixes with a 20% total replacement rate, the 28-day compressive strength of all FA:SS ratios remained within ±5% of the control group, fully satisfying the design requirements of C30 concrete. However, mixes with a higher replacement rate (40%) showed a 7–14% reduction in 28-day compressive strength, which was caused by the reduced cement clinker content, insufficient early hydration products, and weakened matrix continuity.

The strength improvement at moderate dosages was mainly attributed to the synergistic effect of the micro-aggregate filling effect of the composite powder, which optimized the pore structure, and the secondary pozzolanic reaction between the active components of FA/SS and cement hydration products, which enhanced the interfacial transition zone.

Under freeze–thaw cycles, the compressive strength of all specimens decreased with increasing cycle numbers, but FA–SS composite concrete showed significantly lower strength deterioration than the control group. After 200 freeze–thaw cycles, the control group experienced a 31.2% compressive strength loss, whereas the optimal 30% replacement group (FA:SS = 2:1) lost only 12.7% of its initial compressive strength. The 28-day compressive strength of all test groups is presented in Figure 5 These results are consistent with the findings of Chen et al. (2022), who reported that FA–SS composite admixtures at 25–35% replacement rates improved both compressive strength and frost durability through enhanced pore structure refinement and secondary hydration reactions. The strength improvement mechanism can be attributed to the synergistic micro-aggregate filling effect of FA and SS particles, combined with the secondary pozzolanic reaction that produces additional C-S-H gel and densifies the interfacial transition zone (Ye et al., 2018).

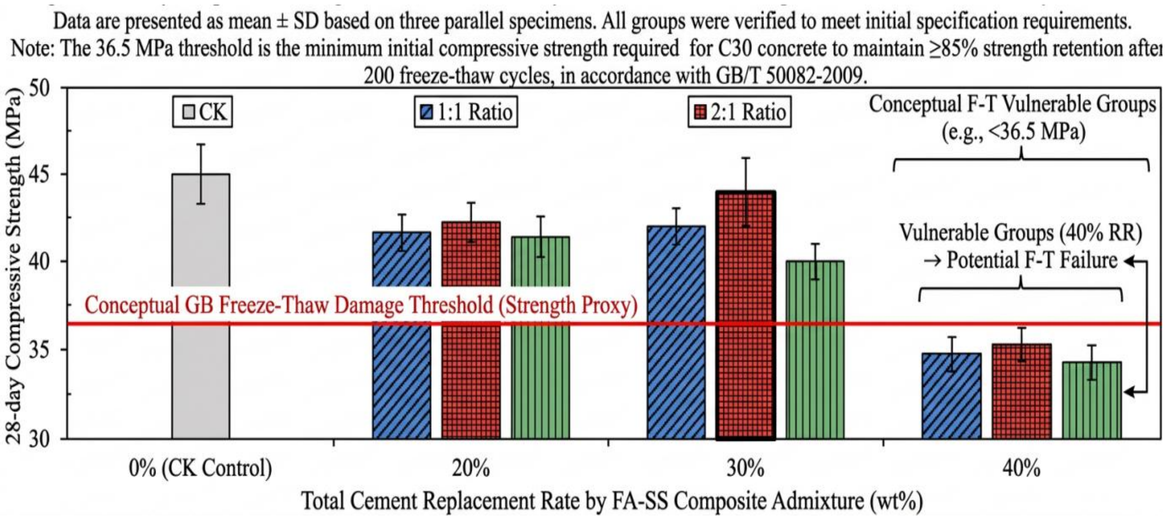

Data are presented as mean ± SD based on three parallel specimens. All groups were verified to meet initial specification requirements.
Note: The 36.5 MPa threshold is the minimum initial compressive strength required for C30 concrete to maintain ≥85% strength retention after 200 freeze-thaw cycles,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

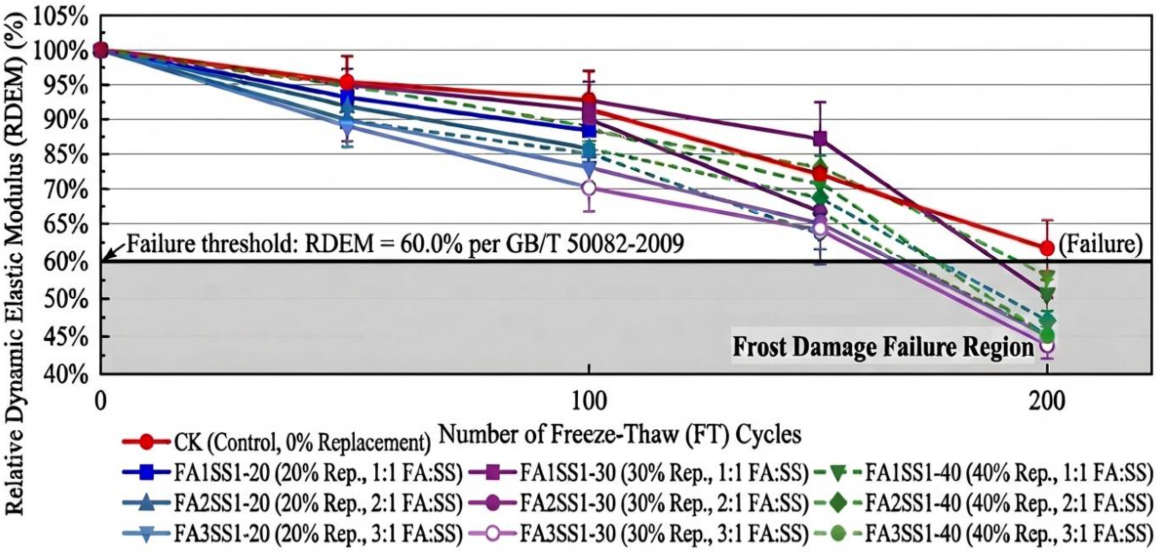
Figure 5.28-day compressive strength of FA-SS blended recycled concrete, with conceptual freeze-thaw vulnerability threshold.

3. Relative dynamic elastic modulus (RDEM)

Relative dynamic elastic modulus (RDEM) was a core non-destructive indicator used to characterize the internal structural integrity and microcrack development of concrete during freeze–thaw cycles. For the control group, the RDEM dropped to 58.7% after 200 freeze–thaw cycles, which fell below the 60% frost damage failure threshold specified in GB/T 50082-2009, indicating severe internal structural deterioration.

In contrast, all FA–SS composite groups with 20% and 30% total replacement rates maintained an RDEM above 60% after 200 freeze–thaw cycles, demonstrating excellent resistance to internal microcrack initiation and propagation. The optimal 30% replacement group (FA:SS = 2:1) retained 86.2% of its initial RDEM after 200 cycles, representing a 27.5% improvement in RDEM retention compared with the control group.

These results confirmed that the FA–SS composite admixture effectively alleviated internal frost-heaving stress, inhibited the development of connected microcracks, and maintained the integrity of the concrete matrix during freeze–thaw cycles. The evolution of RDEM with freeze–thaw cycles for all groups is shown in Figure 6. The RDEM retention of 86.2% at the optimal dosage is notably higher than the 70–80% values typically reported for conventional mineral admixture concrete after 200 freeze–thaw cycles (Zhang et al., 2022), confirming the superior frost resistance conferred by the FA–SS composite system. This enhanced performance can be attributed to the refined pore structure and reduced capillary porosity achieved through the combined filling and pozzolanic effects of the composite admixture, which limits the volume of freezable water and reduces internal frost-heaving pressure (Zhou et al., 2024).



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

4. Mass Loss Characteristics

Mass loss of concrete during freeze–thaw cycles was a direct macroscopic indicator of surface deterioration, which was mainly caused by surface mortar spalling and aggregate exposure under repeated internal freeze–thaw stress. After 200 freeze–thaw cycles, the control group exhibited a mass loss rate of 5.12%, exceeding the 5% failure threshold specified in GB/T 50082-2009, with visible extensive surface mortar spalling and coarse aggregate exposure on the specimen surface.

In comparison, all FA–SS composite groups showed significantly lower surface deterioration and mass loss. The optimal 30% replacement group (FA:SS = 2:1) had the lowest mass loss rate of 1.87% after 200 cycles, representing a 63.5% reduction compared with the control group.

For all test groups, the mass loss rate increased significantly when the total replacement rate exceeded 30%, which was attributed to reduced matrix continuity, increased interfacial defects, and weakened resistance to surface peeling at excessive admixture dosages. The mass loss rate of all specimens after different freeze–thaw cycles is shown in Figure 7.

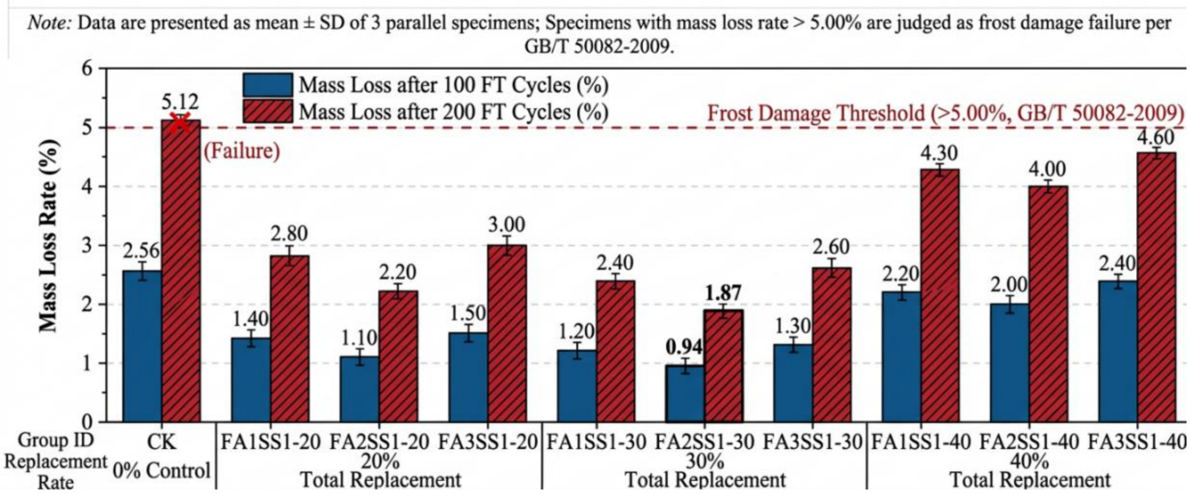

Note: Data are presented as mean ± SD of 3 parallel specimens; Specimens with mass loss rate > 5.00% are judged as frost damage failure per GB/T 50082-2009.

Figure 7. Mass loss rate of specimens after different freeze-thaw (FT) cycles.

5. Frost Resistance Performance under Freeze-Thaw Cycles

Based on GB/T 50082-2009, the frost resistance grade of concrete was determined by the maximum number of freeze–thaw cycles it could withstand while maintaining an RDEM above 60% and a mass loss rate below 5%. The control group only met the requirements of the F100 frost resistance grade and failed to reach F200.

All FA–SS composite groups with 20% and 30% total replacement rates achieved the F200 frost resistance grade, meeting the durability design requirements for infrastructure in the extreme cold environment of Ganzi Prefecture. Among these, the 30% replacement group with an FA:SS ratio of 2:1 demonstrated the best frost resistance performance, retaining 86.2% of its initial RDEM and exhibiting only 1.87% mass loss after 200 cycles—values significantly superior to those of other mixtures within the same grade.

However, the 40% replacement groups only achieved the F150 frost resistance grade, as their RDEM dropped below 60% between 150 and 200 cycles.

6. Overall Performance Evaluation

Considering mechanical strength, frost resistance, workability, and industrial by-product utilization together, the results indicated that a total cement replacement rate of 30% with an FA:SS ratio of 2:1 provided the most balanced performance for concrete in the cold environment of Ganzi Prefecture. This optimal mix achieved simultaneous improvements of 6–8% in 28-day compressive strength, a 63.5% reduction in mass loss rate, and a 27.5% improvement in RDEM retention after 200 freeze–thaw cycles, while maintaining excellent workability for construction.

7. Conclusions

This study was limited to laboratory-scale specimens and a controlled rapid freeze–thaw cycle regime, which simulated the core environmental stress conditions of Ganzi Prefecture but could not fully replicate the long-term combined effects of wind erosion, UV radiation, and traffic loads under real engineering conditions.

In summary, the experimental results demonstrated that the incorporation of FA–SS composite admixtures significantly enhanced the freeze–thaw resistance and mechanical performance of concrete under simulated alpine cold climate conditions of Ganzi Prefecture. Among the investigated mixtures, a total cement replacement rate of 30% with an FA:SS ratio of 2:1 provided the most balanced improvement in compressive strength, frost resistance, structural integrity retention, and workability. Total replacement rates exceeding 40% led to reduced early strength, inferior frost resistance, and poor workability due to reduced matrix continuity and increased internal defects. These findings provided practical guidance for climate-adaptive mix design in durability-critical infrastructure applications in alpine cold regions.

8. Future Work

For practical infrastructure construction in Ganzi Prefecture and similar alpine cold regions, a total cement replacement rate of 30% with an FA:SS ratio of 2:1 is recommended to achieve balanced improvements in frost resistance, mechanical performance, and constructability, while maximizing the utilization of local industrial by-products.

Future research should investigate long-term field performance, full-scale structural testing, and optimization of mix design parameters (such as water-binder ratio and compound admixture systems) to further enhance the frost resistance of FA-SS recycled concrete and confirm its practical applicability in real engineering conditions.

These future investigations will support the practical implementation of industrial by-product-based recycled concrete in real construction environments.

9. Acknowledgements

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