Effect of Combination of Expansive Agent and Fiber on Freeze-Thaw Resistance of High-Strength Concrete at Dry Environment

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Abstract: This study employed a rapid freezing method to investigate the impact of individual additions of expansion agent, steel fibers, and High Elasticity Module Polyethylene Fiber (HEMPF), as well as their combinations, on the freeze-thaw resistance of High-Strength Concrete (HSC). The findings reveal that the non-air-entrained HSC of C80 exhibits excellent freeze-thaw resistance. However, this resistance is sensitive to the curing environment’s humidity. The expansion agent has a negative impact on the freeze-thaw resistance of HSC, while steel fibers and HEMPF fibers have positive effects. Combining HSC with an expansion agent and high elasticity modulus fibers ensures not only high freeze-thaw resistance but also a total alteration of humidity sensitivity, leading to an extended freeze-thaw life of HSC under dry curing conditions.

Keywords: high-strength concrete; freeze-thaw resistance; expansive agent; steel fiber; high elasticity module polyethylene fiber

1. Introduction

The application of High-Strength Concrete (HSC) in major national projects within the arid regions of Northwestern China is an inevitable trend due to its distinct economic and technological advantages, aligning with the developmental requirements of the era. However, the environmental Relative Humidity (RH) significantly impacts the shrinkage deformation of concrete. As Bissonnette et al. [1], Ordinary Portland Cement Concrete (OPC) exhibits approximately five times greater shrinkage deformation at 48% RH compared to that at 92% RH, while HSC demonstrates a more substantial sevenfold increase in shrinkage deformation under similar conditions. Barr et al. [2] reported that with an increase in the strength grade of concrete, shrinkage expands, particularly under lower RH conditions. In the arid Northwestern regions of China, where environmental RH typically ranges from 30% to 55%, common techniques to mitigate HSC shrinkage deformation involve the incorporation of expansive agents and steel fibers [3–6]. Afroughsabet et al. [7,8] investigated the effectiveness of steel fiber in concrete containing expansion cement, finding that the simultaneous addition of steel fiber and an expansion agent can improve the volume stability of concrete under dry conditions. Corinaldesi et al. [9] reported that the expansive agent can significantly enhance the interface quality between the fiber and matrix by increasing adhesion. Pan et al. [10] investigated the effect of hybrid CaO and ettringite-based expansive agents on the mechanical properties and durability of shrinkage-compensating concrete.

Considering the lowest average temperature in northwest China is about −15 °C, it is necessary to account for the adverse effects of freeze-thaw cycles on HSC. Numerous scholars have researched the durability of fiber concrete under freeze-thaw cycles, yielding remarkable results. Sun [11] explored the frost resistance characteristics of fiber concrete, while Kos et al. [12] reported that steel and polypropylene fibers have similar technical
effects in improving the frost resistance of concrete, with polypropylene fibers being a less costly option. Research indicates that the inclusion of steel fibers can enhance the pore structure of concrete [13]. Additionally, the addition of mineral admixtures to fiber concrete can improve its frost resistance [14]. Cao et al. [15] found through experiments that the frost resistance of self-compacting concrete increases with higher fiber content. However, there is a scarcity of literature on the combined impact of expansive agents and fibers on non-air-entrained HSC freeze-thaw resistance, as well as the correlation between HSC freeze-thaw resistance and RH.

This study primarily employs Portland cement and aluminate expansion agents, along with steel fibers or High Elasticity Module Polyethylene Fiber (HEMPF), as reinforcement materials. Through single additions of expansion agent, different fiber materials, and their composites, the study employs a rapid freezing method to investigate the freeze-thaw resistance of non-air-entrained HSC. It explores the formulation technology of HSC that is suitable for application in the arid climate conditions of the Northwest region.

2. Raw Materials and Test Methods

2.1. Raw Materials

Cement (P.II 42.5R): Produced by Jiangnan Cement Factory (Nanjing, China), branded as “Jinning Yang”. Sand: Sourced from Nanjing, it is river sand with a fineness modulus of 2.74, Zone II grading, categorized as medium sand. Aggregate (Crushed Basalt Stone): Obtained from Jvrong City, Jiangsu Province, it has a continuous grading range of 5–16 mm and a maximum particle size of 12 mm. Water: Potable water. Water Reducer: Manufactured by the Jiangsu Institute of Building Science (Nanjing, China), it is a JM-B type naphthalene-based high-efficiency water reducer. It has a water reduction rate exceeding 20%, Na₂SO₄ content less than 2%, and chloride ion content less than 0.01%. AEA Expansive Agent (AEA): Produced by Anhui Chaohu Quick-setting Agent Factory (Chaohu, China), it is an aluminum sulfate expansive agent with a chemical composition detailed in Table 1. Steel Fiber: Manufactured by Jiangxi Engineering Fiber Institute (Nanchang, China), it is GS-2000 helical engineering fiber with an elastic modulus of 200 GPa, a length of 20 mm, and a length-to-diameter ratio of 30. HEMPF: Manufactured in China, it has a density of 0.97 kg/m³, tensile strength of 2.8489 GPa, tensile modulus of elasticity of 73.9 GPa, elongation at break of 3.9%, diameter of 35 µm, oil content of 0.7%, and is cut to a length of 20 mm during usage.

Table 1. Chemical composition of raw materials (wt%).

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SO₃</th>
<th>Fe₂O₃</th>
<th>MnO</th>
<th>TiO₂</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>I.O.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>20.60</td>
<td>5.03</td>
<td>65.06</td>
<td>0.55</td>
<td>2.24</td>
<td>4.38</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.30</td>
</tr>
<tr>
<td>AEA</td>
<td>19.82</td>
<td>16.62</td>
<td>28.60</td>
<td>1.58</td>
<td>26.86</td>
<td>2.66</td>
<td>--</td>
<td>--</td>
<td>0.32</td>
<td>0.30</td>
<td>3.02</td>
</tr>
</tbody>
</table>

2.2. Mix Proportions

Six distinct HSCs were concurrently designed to achieve a compressive strength grade of C80. These include the reference concrete (HSC-1), HSC with single incorporation of expansive agent (HSC-2), HSC with single incorporation of steel fibers (HSC-3), HSC with single incorporation of HEMPF (HSC-4), HSC with composite addition of expansive agent and steel fibers (HSC-5), and HSC with composite addition of expansive agent and HEMPF (HSC-6). The dosage of the expansive agent constitutes 10% of the total weight of binding materials, while the steel fibers account for 2% of the overall concrete volume, and HEMPF comprises 0.1% of the total concrete volume. Table 2 presents the specific mix proportions and physical-mechanical properties of the concrete. It is evident that the combination of expansive agents and fibers exhibits notable reinforcing effects on HSC.
Table 2. Mixture proportions and performance of different concrete.

<table>
<thead>
<tr>
<th>No.</th>
<th>Materials, kg m(^{-3})</th>
<th>W/B</th>
<th>JM-B</th>
<th>Steel Fiber</th>
<th>High Elasticity Module</th>
<th>Slump, mm</th>
<th>Air Content, %</th>
<th>28-Day Compressive Strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement AEA Fine Aggregate Coarse Aggregate</td>
<td>Water</td>
<td></td>
<td>Polyethylene Fiber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSC-1</td>
<td>600 0</td>
<td>610</td>
<td>1134</td>
<td>150</td>
<td>0.25</td>
<td>3.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HSC-2</td>
<td>540 60</td>
<td>610</td>
<td>1134</td>
<td>150</td>
<td>0.25</td>
<td>3.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HSC-3</td>
<td>600 0</td>
<td>785</td>
<td>957</td>
<td>150</td>
<td>0.25</td>
<td>5.0</td>
<td>156</td>
<td>0</td>
</tr>
<tr>
<td>HSC-4</td>
<td>600 0</td>
<td>785</td>
<td>957</td>
<td>150</td>
<td>0.25</td>
<td>6.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>HSC-5</td>
<td>540 60</td>
<td>785</td>
<td>957</td>
<td>150</td>
<td>0.25</td>
<td>5.0</td>
<td>156</td>
<td>0</td>
</tr>
<tr>
<td>HSC-6</td>
<td>540 60</td>
<td>785</td>
<td>957</td>
<td>150</td>
<td>0.25</td>
<td>6.5</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

2.3. Test Methods

2.3.1. Specimen Preparation and Curing

Cement, sand, aggregate, agent, and fibers were dry mixed in a mixer for 1 min, followed by wet mixing with added water for 3 min. After discharge, the slump and air content were measured, and the mixture was manually poured and vibrated to form prism specimens with dimensions of 40 mm \(\times\) 40 mm \(\times\) 160 mm. Each proportion is to make 18 prismatic specimens and to be tested in 3 kinds of RH. The first set of prismatic specimens is used for the flexural strength test, and the second set of prismatic specimens is used for the freeze-thaw cycle test. Therefore, the number of 40 mm \(\times\) 40 mm \(\times\) 160 mm prismatic specimens is at least 108 pieces. MuRu et al. [16] and Sun et al. [17] suggested that the standard antifreeze specimen of 100 mm \(\times\) 100 mm \(\times\) 400 mm is unsuitable for testing external bending stress in the limited space of the freeze-thaw cycle tank. Therefore, a smaller specimen of 40 mm \(\times\) 40 mm \(\times\) 160 mm is recommended for the freeze-thaw test. Comparing test results from two different specifications, it can be concluded that both specimens exhibit the same level of freezing resistance. Moreover, at least 108 cubic specimens sized 100 mm \(\times\) 100 mm \(\times\) 100 mm were prepared to assess the compressive strength of concretes with varied mix ratios at both 28 and 180 days under different RH conditions.

The specimens underwent moist curing, were demolded after 1 day, and then transferred to a standard curing chamber with a temperature of (20 ± 3) °C and RH above 95% for an additional 7 days of curing. Subsequently, the specimens were cured for 180 days under three different conditions: (20 ± 3) °C with RH of 30%, 50%, and above 95%, respectively. Performance tests were conducted at specified intervals under the three curing conditions.

To determine the strength class of the concrete series and the strength growth pattern under different humidity conditions, this paper measured the cubic compressive strength at 28 and 180 days, as well as the flexural strength of prisms at 180 days.

2.3.2. Performance Test

The freeze-thaw test was conducted using the DTR-1 concrete rapid freeze-thaw testing equipment. Following the “rapid freezing method” outlined in the long-term performance and durability standard of ordinary concrete (GB/T 50082-2009) [18], the freezing and melting temperatures of the specimens were set at (−17 ± 2) °C and (8 ± 2) °C, respectively. The melting stage was maintained for not less than one-fourth of the entire freeze-thaw cycle, and each cycle lasted for 2~4 h.

The change in specimen mass after freeze-thaw was measured using an electronic balance with a precision of 0.1 g. The mass variation rate can be calculated using Equation (1).

\[
M = \frac{m_0 - m_t}{m_0}
\]  

where \(m_0\) is the initial mass of sample (g); \(m_t\) is the mass of the sample after the freeze–thaw cycles (g); and \(M\) is the mass variation of the concrete.

The non-metallic ultrasonic testing and analysis instrument NM-4B was used to determine the ultrasonic wave velocity. The relative dynamic elastic modulus of concrete
3. Results and Discussion

3.1. Compressive Strength and Flexural Strength of HSC in Different RH

Figure 1 illustrates the strength evolution patterns of various concrete types under different RHs. As depicted in the figure, both compressive and flexural strengths of all HSC variants exhibit an increase with rising RH. Optimal mechanical properties are observed for HSC under standard curing conditions (RH > 95%). Specifically, concerning the compressive strength of HSC, HSC-5 demonstrates a compressive strength 1.19 times higher than that at 30% RH and 1.02 times higher than that at 50% RH under standard curing conditions. This implies that dry environments negatively impact the development of HSC strength.

Among high-strength concrete with various mix ratios, HSC-5 displays the highest compressive and flexural strengths. Taking standard curing conditions as an example, the compressive strength of HSC-5 is 1.87 times that of the base concrete, and the flexural strength is 2.84 times that of the base concrete. This indicates a positive influence on HSC strength due to the addition of expansion agents and steel fiber.
For HSC with varying mix ratios, the compressive and flexural strengths follow the order: HSC-5 > HSC-3 > HSC-6 > HSC-2 > HSC-4 > HSC-1. This suggests that both the expansion agent and fiber contribute to enhancing the strength of HSC. Notably, the composite of expansive agent and steel fiber results in the highest HSC strength, and the strength of HSC with steel fiber exhibits the least variation in dry environments.

3.2. Freeze-Thaw Resistance of HSC and Its Relationship with Expansive Agents and Fibers

Figure 2 illustrates the influence of the single incorporation of expansive agent, fibers, and their combination on the freeze-thaw resistance of C80-grade HSC. The results indicate that C80-grade HSC possesses a small and non-connected pore structure, leading to extremely low porosity and permeability, as well as minimal freezing water content, thereby demonstrating high freeze-thaw resistance [20].

In the case of the reference HSC-1, a mass increase in the specimens was observed before 500 freeze-thaw cycles due to the continued hydration of cement inside the concrete, with a maximum increase of 0.8%. Moreover, the relative dynamic elastic modulus showed a certain degree of improvement due to hydration effects before 100 cycles. Beyond 500 cycles, surface spalling occurred in HSC-1 specimens, resulting in mass loss. However, its freeze-thaw life could still surpass 1200 cycles, aligning with the findings of Cao et al. [21].

Figure 3 shows the variation in specimen mass and surface damage after 1250 freeze-thaw cycles for HSC with different mix ratios. The concrete specimens in Figure 3a–f exhibit surface sanding and spalling of the hardened cement paste. Additionally, HSC-2 in Figure 3b displays dropped corners, while HSC-6 in Figure 3f exhibits spalling of the mortar, exposure of the coarse aggregate and fibers, and end-breakage.

![Relative dynamic elastic modulus](image1)

![Mass variation](image2)

**Figure 2.** The effect of expansive admixture and fibers on the freeze-thaw durability of HSC.

![Specimens](image3)

**Figure 3.** Mass variation and surface damage following freeze-thaw tests.

Analysis of the graph reveals that for HSC-2, with a single incorporation of AEA expansive agent, despite having a smaller spalling amount on the surface of its specimens during the freeze-thaw process compared to the reference concrete HSC-1, its relative dynamic elastic modulus significantly drops below that of HSC-1 after 300 cycles. Through
calculation, its freeze-thaw life is determined to be 1120 cycles, which is 8% lower than that of the reference concrete. It is evident that the AEA expansive agent has a negative impact on the freeze-thaw resistance of HSC, attributed to the transformation from Afm to Af t within the concrete during the freeze-thaw process, leading to structural microcrack [22]. XRD analysis [19] indicates that HSC-2 with added expansive agent forms more sulfate-aluminate hydrate, and the characteristic peak intensities of Afm (0.846 nm) and Af t (0.971 nm) are 18% and 15% higher than those of the corresponding hydration products in HSC-1.

For HSC-3, with a single incorporation of steel fibers, the structure’s cracking resistance is limited during freeze-thaw due to the crack-arresting effect of the steel fibers. Consequently, its freeze-thaw resistance is significantly improved, and the freeze-thaw life can reach 1285 cycles, a 5% increase compared to the reference concrete.

Regarding HSC-4, with a single incorporation of HEMPF fibers, despite the elastic modulus of these fibers being only 37% that of steel fibers, the crack-arresting effect in concrete depends largely on the average spacing between fibers and the number of fibers in a unit volume of concrete according to the fiber spacing theory [23]. Table 3 illustrates the fiber spacing and quantity in the two types of concrete, showing that the fiber spacing in HSC-4 is reduced by 76% compared to HSC-3, and the fiber quantity is increased by 2800 times. During freeze-thaw, the crack-arresting effect of HEMPF fibers becomes more pronounced, not only restricting the generation of freeze-thaw microcracks in the concrete structure but also suppressing the surface spalling of the specimens. This significantly enhances its freeze-thaw resistance, with a freeze-thaw life of 1295 cycles, a 6% increase compared to the reference concrete. Therefore, it is evident that high elasticity modulus fiber materials have a positive effect on the freeze-thaw resistance of HSC.

Table 3. Fiber Spacing and Fiber Quantity in Two Fiber-Reinforced Concretes.

<table>
<thead>
<tr>
<th>No.</th>
<th>Fiber Density, g cm⁻³</th>
<th>Fiber Diameter, mm</th>
<th>Fiber Length, mm</th>
<th>Fiber Volume Fraction, %</th>
<th>Two-Dimensional Random Distribution</th>
<th>Three-Dimensional Random Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSC-3</td>
<td>7.8</td>
<td>0.650</td>
<td>20</td>
<td>2</td>
<td>5.10</td>
<td>5.75</td>
</tr>
<tr>
<td>HSC-4</td>
<td>0.97</td>
<td>0.035</td>
<td>20</td>
<td>0.1</td>
<td>1.23</td>
<td>1.38</td>
</tr>
</tbody>
</table>

When HSC is compounded with both AEA expansive agent and fibers, the positive effect of fibers on freeze-thaw resistance compensates for the negative effect of the expansive agent. The variation pattern of the relative elastic dynamic modulus during the freeze-thaw process is comparable to that of the reference concrete. This illustrates that the inclusion of fiber could prevent any deterioration in freeze-thaw resistance attributed to the AEA expansive agent.

For HSC-5, with the combined addition of expansive agent and steel fibers, the specimen’s mass remains constant until 1100 cycles, maintaining a freeze-thaw life of 1265 cycles. Similarly, for HSC-6, which incorporates both expansive agent and HEMPF fibers, surface spalling occurs with a mass loss rate comparable to that of the reference concrete beyond 650 cycles, ultimately reaching a freeze-thaw life of 1235 cycles.

3.3. The Freeze-Thaw Resistance of HSC under Dry Conditions

Figure 4 illustrates the freeze-thaw resistance of HSC cured under 50% RH and 30% RH conditions. The results indicate that when HSC is cured in a dry environment, insufficient hydration of cement occurs. This not only affects the growth of hydration products and the densification of pore structure at the microscopic level but also leads to the formation of internal microcracks due to the dry shrinkage of concrete, resulting in a reduction in the freeze-thaw resistance of the reference HSC.
Figure 4. Freeze-Thaw Resistance of HSC Cured under 50% RH and 30% RH Conditions.

Figure 4 illustrates the freeze-thaw resistance of HSC cured under 50% RH and 30% RH conditions. The findings suggest that when HSC undergoes curing in a dry environment, there is insufficient cement hydration. This not only impacts the growth of hydration products and the microscopic densification of the pore structure but also leads to the formation of internal microcracks due to the dry shrinkage of concrete, ultimately resulting in reduced freeze-thaw resistance of the reference HSC.

Figure 5 displays the mass loss and surface damage of HSC with varying mix ratios after undergoing freeze-thaw cycles under 50% RH. HSC-1 and HSC-2, which experienced the most significant mass loss, are used as examples. Figure 5a displays mortar spalling, exposing a large area of coarse aggregate and causing damage and detachment at the end. Figure 5b shows coarse aggregate shedding, resulting in obvious missing ends and severe damage.

(a) HSC-1 (950 cycles)  (b) HSC-2 (835 cycles)
Figure 6 illustrates the mass loss and surface damage of HSC after freeze-thaw cycles with varying mix ratios at 30% RH. The figure illustrates that HSC-1 and HSC-2 suffered significant freeze-thaw damage after 725 cycles, resulting in mortar flaking, large aggregate exposure, and broken ends. HSC-3 remained largely unaffected by the freeze-thaw process. HSC-4 exhibited frost-crisp ends, with mortar flaking on the surface and exposed aggregate and fiber. A detailed view of the aggregate and fiber exposure is shown in Figure 7. Both HSC-5 and HSC-6 displayed mortar flaking with a rough surface and HSC-5 also experienced corner loss. The study compared the damage caused by freeze-thaw cycles on HSC under different RH conditions. The results showed that the severity of freeze-thaw damage on concrete increased with higher RH levels. However, HSC-3 with steel fibers did not exhibit significant damage, regardless of the RH conditions.

![Figure 6. Mass variation and surface damage following freeze-thaw tests (RH 30%).](image)

Figure 7. HSC-4 aggregate and fiber exposure.

For the reference HSC-1 cured at 30% RH and 50% RH after 850 freeze-thaw cycles, there is a notable acceleration in the decrease of the relative dynamic elastic modulus and the rate of mass loss. Moreover, the drier the curing environment, the poorer the freeze-thaw resistance. This demonstrates the sensitivity of HSC’s freeze-thaw resistance to the RH of the curing environment.

In the case of HSC-2, with the addition of an AEA expansive agent, the degradation observed is more severe, attributed to the hydration process of cement and expansive agents in low RH environments. XRD analysis [20] reveals a 163% increase in the characteristic peak intensity of AFm in HSC-2 compared to HSC-1, while the characteristic peak intensity of Aft decreases by 19% when cured at 50% RH. This suggests a pronounced “transformation from AFm to Aft” phenomenon [22] during freeze-thaw cycles, further expanding initially present dry shrinkage microcrack in concrete.

HSC-3, with the addition of steel fibers, exhibits stable freeze-thaw resistance and is not adversely affected by the dry curing environment. Dry curing has a certain adverse
3.4. Relationship between Freeze-Thaw Life of HSC and the RH of Curing Environment

As mentioned earlier, the freeze-thaw resistance of the reference HSC is highly sensitive to the curing environment’s relative humidity (RH). In Figure 8, the relationship between HSC’s freeze-thaw life and curing environment RH is illustrated. The graph indicates a nearly linear correlation between the freeze-thaw life of reference HSC-1 and the RH of the curing environment. In drier conditions, the freeze-thaw life is shorter. Comparing the freeze-thaw life of HSC-1 under standard conditions (>95% RH) as a baseline, the relative freeze-thaw life at 30% RH and 50% RH is only 60% and 78%, respectively. For HSC-2, with the addition of an AEA expansive agent, the curing environment RH significantly influences its freeze-thaw life, with relative freeze-thaw life being only 51% and 62% at 30% RH and 50% RH, respectively. The freeze-thaw life of HSC-3, with the addition of steel fibers, remains unaffected by the curing environment RH. The sensitivity of the freeze-thaw life of HSC-4, with the addition of HEMPF fibers, to the curing environment RH has improved, especially at 50% RH, where its relative freeze-thaw life reaches 95%.

![Figure 8. Relationship Between Freeze-Thaw Life of HSC and Curing Environment RH.](image)

HSC-5, with the combined addition of expansive agent and steel fibers, exhibits a remarkably high relative freeze-thaw life at 30% RH and 50%, ranging from 98% to 104%. Similarly, HSC-6, with the combined addition of expansive agent and HEMPF, shows a relative freeze-thaw life of 81% and 98% at the same RH levels. This indicates that the combined addition of AEA expansive agent and fibers with high elastic modulus effectively addresses the sensitivity of HSC’s freeze-thaw resistance to the curing environment RH. This provides substantial experimental evidence for the application of HSC technology in key engineering projects in arid regions, particularly in northwest China.
4. Conclusions

Based on the experimental results from concrete specimens exposed to freezing and thawing under various relative humidity conditions, it is affirmed that the inclusion of an AEA expansion agent or fibers (specifically steel fibers or HEMPF) leads to an augmentation in both compressive and flexural strength of HSC. Notably, the composite admixture comprising the expansion agent and steel fibers exhibits the highest strength. Different RH influences the strength development of HSC, with lower RH proving more deleterious to this development. Particularly, HSC strength combined with steel fibers displays the least sensitivity to fluctuations in relative humidity.

HSC, with a strength grade of C80, demonstrates robust freeze-thaw resistance even without air entrainment, boasting a freeze-thaw life of at least 1200 cycles. The AEA expansion agent adversely affects the freeze-thaw resistance of HSC, while high-modulus fiber materials, such as steel fibers and HEMPF, positively contribute to this resistance. The synergistic incorporation of the AEA expansion agent and fibers neutralizes the detrimental impact of the expansion agent, thereby safeguarding the freeze-thaw resistance of HSC.

The freeze-thaw resistance of HSC is sensitive to the humidity during the curing process. A drier curing environment correlates with a shorter freeze-thaw life for HSC. The addition of the AEA expansion agent substantially diminishes the freeze-thaw life of HSC under dry conditions, reaching only 51% and 62% at 30% RH and 50% RH, respectively. However, the inclusion of steel fibers has no discernible effect on the freeze-thaw life of HSC under dry conditions. The introduction of HEMPF fibers alone elevates the freeze-thaw life of HSC at 50% RH to 95% of the standard-cured freeze-thaw life. The combination of the AEA expansion agent and fibers nullifies the sensitivity of HSC freeze-thaw resistance to curing environment humidity, yielding a freeze-thaw life at 30% RH to 50% RH ranging from 98% to 104% of the standard-cured freeze-thaw life. Similarly, when the AEA expansion admixture and HEMPF fibers are combined in HSC preparation, the freeze-thaw life at 30% RH to 50% RH ranges from 81% to 98%. Based on the experimental results of this study, the concrete with both AEA expanders and steel fibers had the best frost resistance under dry conditions. This provides a reliable concrete mix ratio scheme for concrete construction projects in the cold and arid climate of Northwest China.

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