Research Article

Bond Behavior of Reinforcing Steel Bars in Thermal Insulation Concrete Exposed to Freeze-Thaw Cycles

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An experimental study on the bond behavior of reinforcing steel bars in thermal insulation concrete (TIC) mixed with glazed hollow beads (GHBs) and exposed to freeze-thaw (F-T) cycles was carried out. In order to investigate the effects of GHBs on freezing and thawing, the experimental results were compared with those of normal concrete (NC). The comparison shows that, after 300 F-T cycles, both bond behavior and mechanical properties of the TIC specimens are better than those of the NC specimens. Furthermore, in order to investigate the mechanism of frost effect on TIC, the CT scanning method was used to investigate the evolution of the inner structure of a TIC specimen exposed to F-T cycles. The CT images show that the deterioration of bond performance and mechanical properties of the TIC specimen appears to be caused by the increase of micropores in the TIC.

1. Introduction

Thermal insulation concrete (TIC) is a new type of concrete containing glazed hollow beads (GHBs) which possess vitrified closed surface and internal honeycomb pores. The study has shown that the TIC can achieve a good balance between thermal insulation and mechanical performance because of its self-insulation property [1].

In cold regions, the damage to an existing reinforced concrete structure caused by freeze-thaw (F-T) cycles could be serious, affecting the usability, safety, and durability of concrete. The resistance of concrete exposed to frost areas has been evaluated in several studies [2–4]. The mechanisms and causes of F-T damage were investigated in other studies. Hasan et al. [5] developed a stress-strain stiffness degradation model for concrete exposed to F-T cycles. Jin et al. [6] investigated the triaxial compressive strength and deformation of plain concrete under F-T cycles. Note that, for structural use, concrete is usually reinforced with steel bars (i.e., rebars). As the temperature changes, microslips may occur at the interface between steel and concrete because of different thermal expansion coefficients. The bond behavior of rebars is very important for a reinforcing element under static or dynamic loading [7], which necessitates the quantification of the deterioration of steel-concrete bond performance due to F-T cycles.

Liu et al. [8] investigated the frost resistance of TIC. They found that, after the exposure to 300 F-T cycles, the dynamic elastic modulus of TIC ranged 60.5–85.2% but deemed satisfactory to structures in cold regions. Liu et al. [9] also tested the bond behavior of TIC after 100 F-T cycles with rebars of different diameters and anchorage lengths and showed that the rebar diameter was the main factor affecting the deterioration of TIC’s bond performance.

There were studies indicating negligible concrete damage due to the inner frost of up to 100 F-T cycles [10]. As a type of multiaperture material, there is surplus water trapped within the pores of concrete structure. When the ambient temperature is below 0°C, the inner water molecule turns into ice and the volume expands by about 9%. This expansion produces tension stress in the concrete inner structure. As reported in the studies [11, 12], if the tensile strength is less than the tension stress, cracks are formed inside the concrete structure. Consequently, the bond between the concrete and the steel is reduced, resulting in a reduction in the reliability performance [13]. Shih showed that cyclic temperature was...
the determining factor that affects the concrete’s maximum bond resistance [14]. This finding is similar to that indicated by others [15, 16].

The bond resistance at the steel-concrete interface consists of three sources: (1) the cement gel’s cementing force, (2) the frictional resistance at the interface, and (3) the mechanical interaction between the intercostal concrete and the rebar’s transverse ribs. The mechanical interaction of a deformed steel bar is determined by the rebar’s surface topography and the intercostal concrete’s mechanical property. Of the three sources, the third one is the most important [17–19]. Thus, the bond property deteriorates if the mechanical performance of the intercostal concrete is degraded by F-T cycles.

The main purpose of this study is to investigate the bond property between TIC and its reinforcing steel bars exposed to F-T cycles. Moreover, in order to make the test results available globally, all tests conducted in this study are in accordance with the international specifications. The combined pullout and strength test was performed to make the assessment on the deterioration of bond performance due to frost. In this study, after F-T cycles, the change in the bond property was quantified in terms of slip, bond strength, splitting tensile strength, compressive strength, relative dynamic modulus of elasticity (RDME), and mass loss rate (MLR). By comparing the failure characteristics of TIC and NC, the usage of insulation aggregates GHB against the adverse effect from F-T cycles can be demonstrated.

Furthermore, previous studies reported that the evolution and random distributions of internal pores and cracks were the critical affecting factors to the frost damage mechanism during the F-T process. Pigeon et al. [20] reported that surface scaling and internal cracking in concrete under the F-T cycles were the two typical damage modes. Several nondestructive methods, such as ultrasonic testing, infrared imaging testing, and computerized tomography (CT) scanning, have been used to observe and evaluate quantitatively the internal damage of concrete after exposed to F-T cycles. Among these methods, the CT scan is deemed an effective one for investigating the internal structure and observing the specimen continuously at different stages of F-T cycles. Based on the CT scan, Promentilla and Sugiyama [21] studied the micropore distribution of different kinds of cement mortar after exposed to F-T cycles. Using the CT scanning, Tian and Han [22] evaluated the damage of concrete after exposed to F-T cycles. Hence, in order to investigate the effect of the number of F-T cycles on TIC, this study uses the CT scan method to evaluate the damage to TIC caused by F-T cycles.

2. Experimental Program

2.1. Materials

2.1.1. Concrete. In this study, ordinary Portland cement and silica fume (SF) were used as the cementitious materials for the TIC, with the properties and constituents listed in Table 1. The 28-day compressive strength of the ordinary Portland cement is 42.5 MPa.

Three types of aggregates were used in the TIC: natural coarse (crushed stone with the particle size of 5–20 mm), natural fine (quartz sand with the fineness modulus of 2.37), and thermal insulation aggregates. As shown in Figure 1, the sieve analysis curves of the coarse and fine aggregates are within the limits of ASTM C33M-16 [23].

As for the thermal insulation aggregates, glazed hollow bead (GHB) being a type of inorganic mineral materials was used, with the physical properties listed in Table 2. It can be made by crushing volcanic rocks into sands and then heat puffed at 800–1000°C, thereby forming the closed-surface spherical particle with inner cavities at 1200°C. The sieve analysis curve of GHB is shown in Figure 1. Polycarboxylate superplasticizer was used in the concrete to reduce the water demand by 35–40%.

2.1.2. Reinforcement. In this study, hot-rolled deformed steel bars with Ø (diameter) = 12 mm were used in the experiments. The material properties of the steel bar were tested according to ASTM-E8M-16 [24]. The test results are summarized in Table 3, and the rib pattern of the steel bar is indicated in Table 4.

2.1.3. Specimens. In this study, two groups of specimens were prepared, with one group intended for the frost effect characterization tests and another group for the bond behavior tests. Totally, 144 cylindrical specimens for the mechanical test and 72 cubic specimens for the pullout test were prepared. For both TIC and NC specimens, the concrete grade is C35 (i.e., compressive strength = 35 MPa) typically. The concrete mixture proportion is shown in Table 5.

The specimens for quantifying the F-T cycling impact on concrete were prepared according to ASTM C192M-16 [25], whose dimensions and physical properties (compressive strength, splitting tensile, and dynamic modulus of elasticity) are summarized in Table 6. In compliance with the RILEM [26], for the pullout tests, 150 mm cubic concrete specimens were prepared. Then, a steel bar was inserted into each specimen along the centerline as shown in Figure 2. Furthermore, in all the specimens, the anchorage length is five times the diameter of the steel bar. Table 7 summarizes the specimen details for the pullout test. All specimens were treated in a standard curing room with the temperature of 20 ± 2°C and the humidity of 95% for 28 days.

2.2. Experimental Method. Comparative tests were conducted on the concrete specimens without exposing to any F-T cycle and those suffering the frost damage. The mechanical properties of the specimens including splitting tensile strength and compressive strength were confirmed based on ASTM C192M-16 [25]. After the curing, the concrete specimens were exposed to the F-T cycles according to ASTM C666M-15 [27]. The duration of the F-T cycle was about 3 hr. In the cool box, the temperature varied between −20 ± 2°C and +20 ± 2°C. For certain specimens, the temperature varied between −15 ± 2°C and 8 ± 2°C. Figure 3
Table 1: Properties and constituents of the cementitious materials.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Ignition loss</th>
<th>Specific surface area (m²/kg)</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>2.86</td>
<td>345</td>
<td>22.53</td>
<td>4.42</td>
<td>2.06</td>
<td>61.7</td>
<td>4.55</td>
</tr>
<tr>
<td>Silica fume</td>
<td>1.95</td>
<td>16,500</td>
<td>87.68</td>
<td>0.93</td>
<td>1.23</td>
<td>0.86</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Figure 1: Sieve analysis curves of the aggregates.

Table 2: Physical properties of glazed hollow beads (GHBs).

<table>
<thead>
<tr>
<th>Particle size (mm)</th>
<th>Bulk density (kg/m³)</th>
<th>Cylindrical compress strength (kPa)</th>
<th>Thermal conductivity (W/(m·K))</th>
<th>24h water absorption (%)</th>
<th>Percentage of closed surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5–1.5</td>
<td>130</td>
<td>209</td>
<td>0.03</td>
<td>23</td>
<td>89</td>
</tr>
</tbody>
</table>

Table 3: Material properties of the steel bar.

<table>
<thead>
<tr>
<th>Strength grade</th>
<th>Diameter (mm)</th>
<th>Cross section area (mm²)</th>
<th>Elongation (%)</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRB400</td>
<td>12</td>
<td>113.1</td>
<td>32.5</td>
<td>408</td>
<td>618</td>
</tr>
</tbody>
</table>

Table 4: Rib pattern of steel bar.

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter (mm)</th>
<th>Measured inside diameter (mm)</th>
<th>Measured outside diameter (mm)</th>
<th>Rib height (mm)</th>
<th>Transverse (mm)</th>
<th>rib width</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRB400</td>
<td>12</td>
<td>11.65</td>
<td>13.74</td>
<td>0.91</td>
<td>7.3</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Concrete mixture proportion.

<table>
<thead>
<tr>
<th>W/C</th>
<th>Gravel (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Cement (kg/m³)</th>
<th>Silica fume (kg/m³)</th>
<th>GHB (kg/m³)</th>
<th>Superplasticizer (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>949</td>
<td>407</td>
<td>379</td>
<td>28</td>
<td>132</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 6: Dimensions and physical properties for the specimens.

<table>
<thead>
<tr>
<th>Concrete type</th>
<th>Frost effect characterization</th>
<th>Specimen dimensions (mm)</th>
<th>Number of freeze-thaw cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIC</td>
<td>Compressive strength</td>
<td>150Φ × 300 L</td>
<td>0, 30, 50, 100, 200, 300</td>
</tr>
<tr>
<td></td>
<td>Splitting tensile strength</td>
<td>150Φ × 300 L</td>
<td>0, 30, 50, 100, 200, 300</td>
</tr>
<tr>
<td></td>
<td>Dynamic modulus of elasticity</td>
<td>100 × 100 × 400</td>
<td>0, 30, 50, 100, 200, 300</td>
</tr>
<tr>
<td>NC</td>
<td>Compressive strength</td>
<td>150Φ × 300 L</td>
<td>0, 30, 50, 100, 200, 300</td>
</tr>
<tr>
<td></td>
<td>Splitting tensile strength</td>
<td>150Φ × 300 L</td>
<td>0, 30, 50, 100, 200, 300</td>
</tr>
<tr>
<td></td>
<td>Dynamic modulus of elasticity</td>
<td>100 × 100 × 400</td>
<td>0, 30, 50, 100, 200, 300</td>
</tr>
</tbody>
</table>
shows the variations of the temperatures measured during the tests.

As required by the RILEM, the steel molds required in the pullout test were designed and the steel bars were embedded into the steel molds horizontally. Thus, the direction of concrete casting is perpendicular to the longitudinal direction of steel bars. After 28 days of curing, for the concrete specimens, the tests were performed. Figure 4 shows the testing equipment used. As seen, one displacement gauge is installed at the unloaded end of the steel bar and another two gauges are installed at the loaded end. These three gauges are attached to the static resistance strain indicators (Type CM-1L-10), which in turn can be accessed by the data acquisition system.

The loading rate would greatly affect the results of the test, which can be determined using the following equation specified in the RILEM [26]:

\[ v = 0.5d^2, \]

where \( v \) is the loading rate and \( d \) is the diameter of steel bar. In this study, the loading rate was set at a constant speed of 72 N/s.

The CT scan method has the advantages of radiation and computer technologies. It can display the inner structure of concrete, the cutting-through process for concrete cracks, and the correlation between aggregates and mortar. Hence, the CT scan method has widely been applied in the engineering field. In this study, an X-ray CT device was used and the digital tomography images were scanned at the same location on the concrete specimens exposed to different F-T cycles. The CT scanning test and scanned cross section are shown in Figure 5. The specimens used in the CT scans have the typical size of 100 mm \( \times \) 100 mm \( \times \) 100 mm. The CT scans were carried out after the specimens were exposed to 0, 50, 100, 200, and 300 F-T cycles. The Image-Pro Plus software [22] was used to analyze the changing process of the mesostructure inside the specimens.

### 3. Results and Discussion

#### 3.1. Effect of Fast F-T Cycles on Freeze-Proof Durability of TIC and NC

##### 3.1.1. Damages to the Surfaces of TIC and NC Specimens

Figure 6 shows the surface conditions for the TIC and NC specimens before and after exposing to the F-T cycles. According to the figure, the surfaces of the specimens are smooth prior to the start of the F-T cycles. The start of the F-T cycles will cause damage to specimen surface. With the increasing F-T cycles, more damages appear on the specimen surfaces. After 50 F-T cycles, a small amount of mortar is scaled in the TIC specimen, while a larger amount of mortar is scaled in the middle of the NC specimen, thereby exposing the quartz sand. After 100 F-T cycles, for the NC specimen, some sands are also scaled, thus exposing the gravel, while for the TIC specimen, the quartz sand is exposed. After 200 F-T cycles, for the NC specimen, almost the entire surface paste spalled and the edges of the specimen broke off, thereby exposing the coarse aggregates, while for the TIC specimen, more surface damage appeared but the gravel was not exposed. After 300 F-T cycles, the NC specimen was completely damaged, while for the TIC specimen, the coarse aggregates were not exposed and there was no damage to the edges of the specimen. As a result, the TIC has a better freeze-proof durability than the NC.
3.1.2. Mass Loss Rate (MLR) and Relative Dynamic Modulus of Elasticity (RDME). Figure 7 shows MLRs of the TIC and NC specimens after exposing to different numbers of F-T cycles. For the TIC specimen, the MLR decreases with the increasing F-T cycles up to 50, but the trend is reversed when the cycle number exceeds 50. For the NC specimen, the MLR increases consistently with the increasing cycle number. This is because in the early stage of F-T cycling the TIC specimen has a small amount of mortar scaled, thus absorbing more water than the mass of scaled mortar [8]. Contrary to the TIC, the NC specimen scales more mortar than the absorbed water.

Figure 8 shows the RDME of the TIC and NC specimens after exposing to different numbers of F-T cycles. With the increase in the number of F-T cycles (N), both specimens will expand gradually and the internal pressure will increase. Hence, the RDME for both TIC and NC specimens becomes smaller. During the process of F-T cycling, the damage in the NC and TIC specimens starts from the destruction of their pore structures. Note that the RDME for the NC specimen becomes steady at 58.94% of that corresponding to \( N = 0 \), at \( N \approx 200 \). For the TIC specimen, there are three distinct RDME variation periods: (1) initial period \( (N \leq 100) \): the RDME decreases by about 6.08%; (2) accelerating decreasing period \( (N = 100–175) \): the RDME decreases by about 26.23%; and (3) steady period \( (N \geq 175) \): the RDME decreases by about 5.21%. After 300 F-T cycles, the RDME remains at a constant 62.84% of the RDME corresponding to \( N = 0 \). The F-T cycling damage of the TIC specimen is probably caused by the addition of GHBs which act as the solid air-entraining agent thereby improving the concrete freeze-proof durability. According to the mechanisms proposed in earlier studies [28, 29], when exposed to F-T cycles, the inner structure of concrete is likely to be damaged by both hydraulic and frost-heaving pressures, resulting from the moisture migration and volume expansion. In the initial stage of the F-T cycles, the inner structure of the TIC specimen contains GHBs, contributing to an extraroom for pore water to expand. On that basis, it dilutes the internal

**Figure 4:** Details of the pullout specimen and testing equipment.

**Figure 5:** (a) CT scanning test and (b) scanned cross section.
pressure generated during the ice formation and prevents concrete cracking.

3.1.3. Compressive Strength and Splitting Tensile Strength. Table 8 shows the compressive and splitting tensile strengths of the TIC and NC specimens after exposing to different numbers of F-T cycles ($N$). According to the table, with the increasing $N$, both compressive and splitting tensile strengths decrease. For the TIC specimen, when $N = 300$, the compressive strength reduces by 53% than that, with $N = 0$, while the splitting tensile strength decreases by 60%. In contrast, for the NC specimen, the compressive strength reduces by 64% and the splitting tensile strength decreases by 66% when $N = 100$. Furthermore, for the NC specimen as shown in Figure 9, there are cracks on the surface of the
Table 8: Compressive and splitting tensile strengths of the TIC and NC specimens after exposing to different numbers of F-T cycles.

<table>
<thead>
<tr>
<th>Strength Type</th>
<th>Number of freeze-thaw cycles</th>
<th>TIC</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive (MPa)</td>
<td>0</td>
<td>37.82</td>
<td>34.20</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>35.77</td>
<td>26.44</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>33.82</td>
<td>22.93</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>28.69</td>
<td>12.22</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>23.16</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>17.86</td>
<td>—</td>
</tr>
<tr>
<td>Splitting tensile (MPa)</td>
<td>0</td>
<td>4.10</td>
<td>3.02</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>3.82</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3.49</td>
<td>1.87</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>3.06</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>2.40</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>1.60</td>
<td>—</td>
</tr>
</tbody>
</table>

3.1.4. Result and Analysis of Mesoscopic CT Test. Figure 10 shows the mesoscopic image of the TIC specimen after exposing to different numbers of F-T cycles (N). According to the figure, prior to the beginning of F-T cycles, there are some micropores and fractures in the specimen. With the increasing N, larger micropores are formed in the specimen, such as Points A and B in Figure 10. For example, before the start of F-T cycles, there are two small holes at Point A. Then, after 100 F-T cycles, due to the persistent fatigue damage, the two small holes become one large hole at Point A with an area ≈50 mm². After 200 F-T cycles, the hole at Point A becomes the biggest hole in the TIC specimen. This phenomenon is due to the transformation of the pore water from liquid state to solid state and then back to the liquid state. At every stage of the transformation, frost-heaving force is produced. Hence, the specimen becomes loose and breaks up. In fact, some pores develop into cut-through mesofractures.

In the CT images, the micropores are mainly on the cemented surface of aggregates and mortar, i.e., the interface transition zone. This phenomenon was also reported by Chen et al. [30] and can be explained by the fact that the interface transition zone is the weak part in the concrete as demonstrated by Vargas et al. [31].

With the purpose to analyze the pore structure of TIC specimens, the binarization processing was conducted on the original CT images. As shown in Figure 11, in the CT images before and after binarization processing, the pore structure of the TIC specimen in the binarization picture was marked as black and other parts of concrete was marked as white. Then, by using the software Image-Pro Plus to analyze the CT images, the characteristics of the micropores were determined. Table 9 shows the distributions of pore areas in the TIC specimen after exposing to different numbers of F-T cycles. It shows that the number of micropores increases significantly when the number of F-T cycles rises. After 300 F-T cycles, there are 104 micropores which represent a 267% increase compared to 0 F-T cycles. This indicates that the number of F-T cycles has an obvious effect on the internal pore structure of the TIC specimen. From Table 9, it can also be seen that the micropores with an area <1 mm² account for about 41–69.7% of the total micropore area after exposing to different numbers of F-T cycles. With the increasing F-T cycles, smaller micropores (area <1 mm²) increase first and then decrease, accompanied with increasing larger pores (area >1 mm²). This is an indication that, with the increase in the number of F-T cycles, the pores keep developing and merging, thereby forming larger pores.

3.2. Deterioration of Bond Performance due to F-T Cycles

3.2.1. Effect of F-T Cycles on the Interface between Steel Bar and TIC. Figure 12 shows the images of the interface between the steel bar and the TIC specimen after exposing to different numbers of F-T cycles. The figure shows that prior to the beginning of the F-T cycles, the deformed bar is within the recess at the interface. With the increasing F-T cycles, the interface becomes more smooth gradually. After 300 F-T cycles, the bond interface becomes a smooth surface. Before that, frost exists in the TIC specimen and many aggregates appear at the interface. After the pullout test, some aggregates experience splitting damage, indicating that a good bond strength between the aggregates and the cement remains. However, with the frost damage, the aggregates break off from the cement. From the microscopic point of view, concrete is a type of porous material. So, at the interface between cement and aggregates, there is a large amount of pore water. As the temperature is below 0°C, the pore water transforms into ice and the volume expands by 9%. This is the main reason why the interface becomes more smooth due to F-T cycles.

3.2.2. Ultimate Bond Strength and Bond Slip. According to this study, all specimens failed during the pullout test, in which the rebar was pulled out from the concrete and the intercostal concrete failed by shear. Table 10 shows the bond behavior of the steel bar in the TIC and NC specimens from the pullout test, including the ultimate bond strength (τ_u), ultimate bond slip (S_b), and failure mode. Based on the pullout test results, the bond stresses of the steel bars in the TIC and NC specimens are constant within the anchorage length. Hence, an average bond strength τ can be used as calculated by

$$
\tau = \frac{P}{\pi d l}
$$  (2)
where $P$ is the applied load, $d$ is the diameter of the steel bar, and $l$ is the anchorage length.

According to the experimental data, the relationships between the ultimate bond strength ($\tau_u$) and the F-T cycle number ($N$) for the TIC and NC specimens can be expressed as

\[
\tau_u = 0.0002N^2 - 0.0925N + 27.653
\]

for the TIC specimen with $R^2 = 0.9844$,

\[
\tau_u = 0.0007N^2 - 0.2327N + 30.784
\]

for the NC specimen with $R^2 = 0.993$.

where $R^2$ is the correlative coefficient.

3.2.3. Influence of Freeze-Thaw Cycles on Relative Bond Strength. Earlier studies showed that the compressive and splitting tensile strengths of NC greatly impacted the bond strength [32–34]. In this study, for the TIC, the compressive strength-bond strength and splitting tensile strength-bond strength relationships were found to be similar to those obtained by Liu et al. [9] for TIC; for example, as the compressive strength of the TIC decreases by 19.3%, the bond strength decreases by 15.4%. With the purpose to dilute the various impacts of compressive strength of TIC specimens on bond strength, in this study, a parameter known as the relative bond strength ($r_d$) is proposed to quantify the bond strength deterioration after F-T cycles [35–38], which is expressed by

\[
r_d = \frac{r_u}{\sqrt{f_u}}
\]

where $f_u$ is the compressive strength of concrete.

Table 11 shows the $r_d$ values of the TIC specimen after exposing to different numbers of F-T cycles. With the increasing F-T cycle number, $r_d$ decreases. This is due to the damage of the porous concrete material caused by the F-T cycles. The cause for this phenomenon is that there is abundant free water in concrete confined within pores. Hence, the freezing of water leads to expansion within the confined space of pores, causing the development of stresses that contribute to cracking. Then, the concrete crumbles and

Table 9: Distributions of pore areas in the TIC specimen after exposing to different numbers of freeze-thaw cycles.

<table>
<thead>
<tr>
<th>Pore area (mm²)</th>
<th>Number of freeze-thaw cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>&lt;1.0</td>
<td>16</td>
</tr>
<tr>
<td>1.0–2.0</td>
<td>10</td>
</tr>
<tr>
<td>2.0–3.0</td>
<td>1</td>
</tr>
<tr>
<td>3.0–4.0</td>
<td>5</td>
</tr>
<tr>
<td>4.0–5.0</td>
<td>1</td>
</tr>
<tr>
<td>&gt;5.0</td>
<td>6</td>
</tr>
</tbody>
</table>
3.2.4. Influence of Freeze-Thaw Cycles on Bond-Slip Curves.
Figure 13 indicates how F-T cycles impact the bond slip of the TIC. It shows that a bond-slip curve generally contains three segments: ascending, descending, and residual. The shape of the curve is controlled by the ultimate bond strength $\tau_u$, peak slip $s_u$, and residual shear strength $\tau_r$ [34]. The F-T cycles generally do not impact the shape of the bond-slip curve of TIC, as the curve still contains the three parts after 300 F-T cycles. However, with the increasing F-T cycles, $\tau_u$ and $\tau_r$ increase, while $s_u$ decreases. As can be seen from Figure 13, the bond stress corresponding to the peak of each bond-slip curve represents the bond strength. Obviously, as F-T cycles repeat, the bond strength decreases, while the slip corresponding to the bond strength increases.

The resistance of steel bar against the pullout is mainly from the adhesion force, friction force, and the mechanical interaction force between reinforcing steel bar and concrete. Since the adhesion force vanishes in the early loading stage when slip occurs, the resistance to pullout comes from the mechanical interaction force and friction force only [38]. Concrete deterioration due to the exposure of rapid F-T cycles weakens the friction force and the mechanical interaction force between steel bar and concrete and lowers the resistance against pullout. On that basis, the bond strength between steel bar and concrete decreases rapidly with increasing F-T cycles.

3.2.5. Change of Porosity with the Ultimate Bond Strength of TIC. Figure 14 shows the relationship between the number of pores and the ultimate bond strength of the TIC specimen. As shown in the figure, the pore number increases with increasing F-T cycles and a negative relation is noted between the number of pores and the ultimate bond strength. The porosity of concrete greatly impacts the bond strength.
performance due to pore expansion and cracks which degrade the mechanic properties of concrete.

3.2.6. Differences in Deterioration of Bond Performances between TIC and NC. Figures 13 and 15 show the bond-slip curves of TIC and NC specimens, respectively, after exposing to disparate numbers of freeze-thaw cycles. After the number of F-T cycles reaches 200, the decrease in the RDME of the NC specimen is more than 60%. So, the pullout test was terminated at 200 F-T cycles. The bond-slip curves of both TIC and NC specimens are similar, involving three stages: (1) ascending, (2) descending, and (3) residual. However, due to the differences in the inner structures between TIC and NC specimens, the deterioration in the bond performance of the damaged TIC specimen is less than that of the NC specimen. With the increasing F-T cycles, during the ascending stage, the TIC bond-slip curves show a downtrend due to the frost damage. Furthermore, during the descending stage, the bond-slip curves of the damaged concrete present a larger degree of smoothness compared with those of the undamaged concrete. After 300 F-T cycles, the ultimate bond strength decreases from 10.32% to 50.73% and the corresponding increase of the slip is 21.87–98.44%. Either the undamaged specimens or the frost-damaged specimens, the failure mode belongs to shear.

In contrast with the TIC specimen, there is a higher degree of deterioration in the NC specimen. After 100 F-T cycles, during the ascending phase, the slope of NC bond-slip curves decreases faster than that of the TIC curves. Moreover, during the descending stage, the NC curves descend faster than the TIC curves. This is due to the shifting of the splitting failure mode in the frost-damaged specimens after 100 cycles (Figure 15). After 100 F-T cycles, the ultimate bond strength decreases from 18.69% to 54.57% and the corresponding increase in the slip is 23.08–72.31%. This suggests that it is better to use TIC rather than NC in cold regions.

The above results show that the TIC has better frost resistance than the NC. As shown in Figure 16, the GHBs in TIC specimens are acting as a type of solid air-entrained agent preventing the harmful effects of frost.

In addition to the frost damage, the concrete also undergoes a permanent deformation which leads to an additional pore space, subsequently filled with water once the concrete becomes saturated. Therefore, several F-T cycles cause a progressive damage to the concrete, as demonstrated in Figure 16. However, due to the internal honeycomb pores and vitrified closed surfaces, GHBs have a good ability to sustain water. Hence, the special pore structure is able to interrupt the microcrack development caused by the water moisture migration and expansion during the freezing and expanding of the inner pore water of TIC.
4. Conclusions

This paper discusses the effect of F-T cycles on the bond performance of the steel bar embedded in the TIC specimen. Based on this study, the following main findings are offered:

(1) The compressive and splitting tensile strengths of TIC are more sensitive to frost damage than the RDME. After 300 F-T cycles, the RDME of the TIC specimen is constant at 62.84% and the MLR is less than 5% of the initial mass. Furthermore, the compressive strength and splitting tensile strength decrease to 53% and 60.9% of the initial strength, respectively. Hence, it may not be sufficient to evaluate the frost resistance of TIC considering only the RDME.

(2) After 300 F-T cycles, the ultimate bond strength of TIC decreases by 50.7%, whereas the slip at the peak pullout load increases by 98.4%. Moreover, as shown by the bond-slip curves, the bond stiffness is less and the bond strength is lower. After 300 F-T cycles, the bond-slip curves of the TIC specimen show that the characteristic failure mode is shear. There is no significant change to the characteristic failure of the TIC exposed to F-T cycles after the pullout test. This indicates that the TIC is satisfactory in terms of frost resistance.

(3) The interface transition zones are the weak zones in the inner concrete. After 300 F-T cycles, the number of micropores in the concrete increases 267%. The mechanical properties and bond performance degradation are mainly caused by the increasing number of micropores in the concrete.

(4) The thermal insulation aggregate GHB appears to be beneficial as it could reduce the frost damage caused by F-T cycles. After 300 F-T cycles, both the bond behavior and the mechanical properties of the TIC specimen are better than those of the NC specimen.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

However, the opinions expressed in this paper are solely of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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