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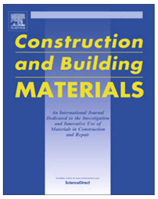

Bond performance of thermal insulation concrete under freeze–thaw cycles

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HIGHLIGHTS

- TIC is utilizable for structures in cold areas due to adequate frost resistance.
- An expression is developed to describe the bond strength of damaged TIC.
- The porous structure in GHB is beneficial to the frost-proof durability of TIC.
- The rebar diameter leads to apparent deterioration and shift of bond property.

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ABSTRACT

Thermal insulation concrete (TIC) mixed with a sufficient volume of glazed hollow beads (GHBs) is an innovative material and has been proven to achieve an excellent balance between the mechanical and thermal insulation performances due to its self-insulation property. However, the bond between the reinforcing bars (rebars) and the TIC must be good enough in long-term sense for wide practical applications using the TIC. This paper focuses on the experimental study on the deterioration of the bond property between the TIC and rebars in freeze–thaw environment. A total of 132 pullout specimens and 216 cubic specimens made of TIC were prepared, which cover three concrete strength grades, three rebar diameters, and six anchorage lengths. Parts of the specimens were exposed to various number of rapid freeze–thaw cycles prior to their failure.

The combination of pull-out and mechanical performance test was carried out to assess the frost damage on bond performance. The frost damage on bond property was quantified based on the bond strength, slip, splitting tensile strength, and relative dynamic modulus of elasticity. The usage of GHB against the harmful effects of freeze–thaw cycles was also analyzed by comparing the failure characteristics of normal concrete to that of the TIC. Interestingly, the bond performance of the TIC is found to be affected by the rebar diameter and anchorage length, rather than the concrete strength. The rebar diameter results in the apparent decrease of bond strength and the variation of failure modes. Lastly, an analytical expression was developed to relate the bond strength with the splitting strength of damaged TIC, which considers the effects of rebar diameter and anchorage length. The proposed equation correlates well with the experimental results.

1. Introduction

The enormous building energy consumption and the greenhouse gas emission are becoming as inevitable issues to the global climate change. More than 0.69 billon of hydrocarbon energy consumption comes from the public and residential buildings in China [1]. Due to the thicker insulation layer and the more complex construction technology required in cold areas, reducing the thermal conductivity of structural material is deemed as an effective solution to achieving energy efficiency by altering the thermal physical properties of building envelopes [2].

Thermal insulation concrete (TIC) mixed with a sufficient volume of glazed hollow beads (GHBs) is an innovative material and has been proven to achieve an excellent balance between the mechanical and thermal insulation performances due to its self-insulation property. The compressive strength of TIC ranges from

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20 to 50 MPa, which is similar to the strength of the normal concrete (NC). The thermal conductivity of TIC ranges between 0.30 and 0.50 W/(m K), which is obviously lower than that of NC having the thermal conductivity up to 1.51 W/(m K) according to the China's code [3]. The insulation property of TIC is apparently superior to the conventional structural concrete.

Several researchers have investigated the behavior of TIC including mix design, thermal insulation properties, microstructure [4], and mechanical properties [5]. Relevant research, such as mechanical properties and seismic behavior of TIC mixed with construction waste, was carried out [6–8], where the stress–strain constitutive relationship and failure behavior of TIC were also discussed. The available research results showed that the behavior of NC and TIC are very similar under uniaxial loading conditions and that TIC is more ductile than NC for the same strength grades. Previous research on TIC also looked at the bond performance between reinforcement and TIC [9], in which a relation between the bond strength and the tensile strength was proposed based on the experimental results. In China, a TIC with C35 strength grade had been used in a 12-floor residential building with frame-shear wall [10], where an 82.6% reduction for coal consumption compared with normal concrete buildings was obtained.

In cold environment, reinforced concrete structures are often connected with temperature cycles that reduce the expected durability of the system. To evaluate the durability of the concrete, the frost resistance of TIC had been tested previously [11], which shows that the dynamic elastic modulus of TIC ranges from 60.5% to 85.2% under 300 cycles being considered satisfactory to the structures exposed to cold environment. However, not only the material, but also the bond between the reinforcing bars (rebars) and the TIC must be good enough in long-term sense for wide practical applications using the TIC. It can be concluded from the previous research [12–14] that the residual load-carrying capacity of frost-damaged concrete needs to be quantified in terms of bond properties. Fagerlund showed that the bond capacity and slip at the maximum bond strength changed significantly by frost damage [12]. Experimental results from Petersen showed that the internal damage's location affected notably the bond decreases and the slip increase [13]. Hanjari showed that the relations for undamaged concrete could not be used directly for frost-damaged concrete [14].

There are several kinds of mechanisms explaining the frost damage in concrete including "Hydraulic pressure" [15,16] and "Microscopic ice lens growth" [17]. However, much less attention has been given to the effect of frost damage on the bond performance of concrete. Based on the limited available publications, two major viewpoints can be summarized as follows. One is that the frost damage on bond performance was quantified by the number of freeze–thaw cycles [18]. Shih regarded cyclic temperature as the decisive factor affecting the maximum bond resistance of concrete. Similar results can be obtained from the studies of Ji et al. [19] and He et al. [20]. Another viewpoint from the previous research is that the damage degree depends more on the material properties and internal structure of concrete than on the exterior environment such as the number of freeze–thaw cycles [13,21,22]. Meanwhile, the internal structure of concrete may be strongly influenced by the frost damage caused due to the increase of inner pressure and the associated micro cracks.

For the reasons mentioned above, a series of experiments were carried out in this study to investigate the deterioration of bond property between TIC and reinforced bars. Based on the conclusions obtained from our previous research, which agrees with the second viewpoint, the study in this paper focuses on the severity of the damage. That is, the changing in bond property, rather than the correlation between the damage level and the number of freeze–thaw cycles, was used to quantify the frost damage.

The combination of pull-off and strength test was carried out to assess the frost damage on bond performance. In this study, the change of bond property after freeze–thaw cycles was quantified based on the bond strength, slip, compressive strength, splitting tensile strength, and relative dynamic modulus of elasticity. The usage of GHB against the harmful effects of freeze–thaw cycles was also analyzed by comparing the failure characteristics of normal concrete to that of the TIC.

2. The experimental program

In this study, several tests were carried out to evaluate the frost-damaged concrete and the undamaged concrete specimens. The first kind of specimens were exposed to 100 rapid freeze–thaw cycles prior to their failure. Besides, parts of the specimens with C35 strength grade were exposed to 30, 60, and 100 rapid freeze–thaw cycles to investigate the mechanical and bond responses against the various freeze–thaw cycles.

The frost damage on the bond property between reinforcement and concrete was experimentally determined by the pull-out test recommended in RILEM [23]. The deterioration on mechanical properties, including compressive strength and splitting tensile strength, was determined by the strength test according to Chinese Standard [24]. The dynamic modulus of elasticity, intended to assess the frost damage on TIC and explain the frost-resistance mechanism, was experimentally determined by the test recommended in Chinese Standard [25].

2.1. Materials and specimens

2.1.1. Concrete

In this study, the mechanical properties of TIC using three different strength grades (C30, C35, C40) were evaluated. The mixture proportions for the three different strength grades were designed and tested six times for each strength grade. The average result from the six specimens was used in each experiment. The concrete mixture proportions for the test specimens are shown in Table 1, in which the GHB particles were used as thermal insulation aggregates to reduce the thermal conductivity [6]. Polycarboxylate high-efficiency water-reducer was used in the mixtures for this study as the chemical additive with water reducing rate of 35–40%.

2.1.2. Reinforcement

In this research, hot-rolled ribbed bar (HRB) was chosen, covering three different nominal diameters of reinforcement. All ribbed bars had similar rib pattern, as shown in Table 2. The geometrical dimensions such as the spacing between ribs (s_R), the rib height (h_r), and the tensile elongation (δ_5) are presented in Table 2 along with the mechanical properties of reinforcement.

2.1.3. Specimens

Two kinds of specimens were fabricated for distinct research purposes: cubic concrete specimens for frost effect characterization tests; pull-out specimens for bond performance tests. The average result from six specimens was used for each experiment. The specimens for characterizing the frost effects were prepared according to the Chinese Standard [24,25]. In total, 216 TIC and 72 NC specimens were cast in steel forms, as summarized in Table 3. The specimens were cured in a standard curing room at a temperature of 20 ± 2 °C and 95% humidity for a period of 28 days.

For the pull-out tests as recommended in RILEM, concrete cube specimens with the unit dimension of 150 mm were used and a bar was inserted along any principal axis of the cubic specimen.

For comparison purposes, a total of 132 pull-out specimens were prepared, which cover three concrete strength grades (C30, C35, and C40), three rebar diameters ($\varnothing$12, $\varnothing$18, and $\varnothing$25), and six anchorage lengths. The anchorage length of the reinforcement is equal to 5 times the bar diameter. While the remaining part of the reinforcement was insulated from the concrete by means of a plastic sleeve. Besides, the embedded length, ranging from 1.5 to 12.5 times the bar diameter, was used to analyze its influence on the degradation of bond property, as summarized in Table 4.

The steel molds adopted in the pull-out testing were designed according to the requirement of Chinese Standard for Test Method of Concrete Structures [26], where the steel bars were embedded horizontally in the steel molds. As such, the casting direction was perpendicular to the longitudinal direction of bars. The tests were carried out at the age of 28 days, using the equipment shown in Fig. 1.

2.2. The experimental method

In this study, several tests were made on the reference specimens and frost-damaged concrete. The compressive and splitting tensile strengths were tested according to the GB/T 50081 Standard [24]. YAW-1000 compression-testing machine with microcomputer controlled electro-hydraulic servo system was used