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Effect of High Temperature on the Bond Performance of Reinforcing Bars in Inorganic Polymer Concrete

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Abstract

This paper discusses the effect of the compressive and tensile strength of inorganic polymer concrete (IPC), protection layer thickness and bonded length of reinforcing bars (rebars) on the bond performance between IPC and rebars through laboratory tests of IPC at high temperatures. In addition, the bond performances of IPC and ordinary concrete at high temperatures are compared. The experimental results indicate that IPC at high temperatures exhibits superior bond performance with rebars compared with ordinary concrete. As the temperature increases, the reduction in the IPC-rebar bond strength exhibits similar behavior as the reduction in the compressive and tensile strengths of IPC. Thin protection layers contribute to significant degradation of the IPC-rebar bond strength at high temperatures. The degradation of the bond strength is affected by the rebar bonded length at room temperature but is not influenced at high temperatures. The analytical expression of the IPC-rebar bond strength at high temperatures can be derived by best fitting the experimental results. Based on the expression of the ultimate bond strength and the expression of rebar slip, a two-segment regression analysis is performed to obtain the local bond-slip relationship of rebars in IPC after exposure to high temperatures. This study provides theoretical contributions to the engineering application of IPC.

1. Introduction

The bond characteristics of reinforcing bars (rebars) in concrete at high temperatures are important for maintaining structural safety in fire. Numerous studies of the bond characteristics between rebars and ordinary concrete have been performed. Some recent studies (Morley and Royles 1980; Yin et al. 2011) demonstrated that the structural strength of concrete decreased as the temperature increased; at higher temperature, the degradation of the concrete-rebar bond strength (also be called shear strength) was more significant. Morley and Royles (1985) investigated the different behaviors of compressive and tensile strengths for different temperatures; at 250°C, the bond strength of concrete was related to its compressive strength. Similar results were obtained by Diederichs and Schneider (1981) that the bond strength exhibited similar behavior as the compressive strength at high temperatures. El-Hawary et al. (1996) developed an analytical model for calculating the bond strength through laboratory tests at high temperatures.

Inorganic polymer concrete (IPC) is a new type of “green concrete” that has gained a significant amount of attention. Due to its valuable characteristics, such as fast setting, early strength and chemical resistance, IPC has been diversely applied in engineering and the building industry (Tian et al. 2011; Lloyd, and Rangan 2010). Particular attention has been paid to the bond performance between IPC and rebars. Sofi et al. (2007) discovered that the bond properties of IPC corresponded to its compressive and tensile strengths. Sarker (2011) and Zhang et al. (2016) found that IPC exhibited superior bond performance with rebars compared with ordinary concrete. Sarker (2011) demonstrated that the bond performance between IPC and rebars improved with the increases of the protection layer thickness and compressive strength and that the bond performance was positively related to the ratio of the protection layer thickness to the rebar diameter. Compressive and tensile strengths, rebar properties, the protection layer thickness and the bond strength were evaluated by Zhang et al. (2016) and developed a local τ-s relationship. These studies primarily focused on the bond behavior in room temperature. Minimal attention has been put on the bond performance

Fig. 1 Diagram of pullout test specimens.
This paper focuses on the effect of the compressive and tensile strengths, relative protection layer thickness, and bond strength of IPC on the bond performance of rebars in IPC at high temperature, which is also compared with the bond behavior of ordinary concrete with rebars at high temperatures. The expression for the IPC-rebar bond strength at high temperatures and the local bond-slip relationship, which are obtained through regression analysis, provide a theoretical basis for the engineering applications of IPC.

### 2. Experimental investigation

#### 2.1 Specimen design

The test specimens employed in the pullout tests are based on the recommendation of RILEM-CEB-FIP. The specimens are 150×150×150 mm concrete cubes with rebars anchored at the center of each specimen. The type of rebar is HRB400, and the rebar diameters are 10, 14 and 18 mm. As illustrated in Fig. 1, the free end is close to the bonded section of the rebar. The unbonded rebar section was treated at high temperatures as follows: apply a 2 mm fire retardant coating to the rebar surface, wrap the rebar in 12 mm glass fiber, and insert the rebar into a high aluminum tube to prevent heat loss.

To avoid damage at the loaded end of the specimen during the pullout tests, the bonded length of the rebars was set to 60 mm, 75 mm and 90 mm (i.e., four times to seven times of the diameter \( d \)), and the length of the high aluminum tube for the unbonded section was 90 mm, 75 mm and 60 mm.

Four batches of specimens were prepared for laboratory tests. The specimens in Batch A, Batch B and Batch C were tested to evaluate the effect of the mechanical strength, relative protection layer thickness and bonded length on the bond performance of IPC after exposure to high temperatures. The specimens in Batch D were tested to compare with the bond performances of ordinary concrete. A total of 342 specimens were tested. The 342 specimens included 22 temperature test specimens, 80 pullout type specimens, 120 compressive test specimens, and 120 splitting tensile test specimens. Three mixture designs were used to change the mechanical strengths of the specimens. Specimens with different relative protection layer thicknesses and bond strengths were tested for comparative analysis. Five temperature settings were used: room temperature (25°C), 200°C, 400°C, 600°C and 800°C. To control the experimental errors, two pullout type specimens were fabricated for each temperature setting within each test group. If the difference between the two results exceeded 15%, the specimens were remade. For each temperature setting within each test group, three specimens were tested for compressive strength, and another three specimens were tested for tensile strength. The specimen characteristics were summarized in Table 1.

#### 2.2 Materials

IPC was composed of slag, fly ash and alkaline activator. Commercially available F class (low calcium) fly ash with a density of 2.187 g/cm³ and normal slag with a density of 2.9 g/cm³ and a specific surface area of 470m²/kg were prepared. The main chemical properties of fly ash and slag determined by XRF were tabulated in Table 2.
Table 2. The alkaline activator was sodium silicates (Na$_2$SiO$_4$) solution developed with original sodium silicate solution, sodium hydroxide (NaOH) flakes of 98% purity and water. The modulus (SiO$_2$/Na$_2$O) of activating agent was 3.129 (SiO$_2$=25.72%, Na$_2$O=8.21%, and water=66.07%). River sand (fineness modulus=2.58) and coarse limestone aggregates (gravel) with size of 5-15 mm were utilized. The IPC mix variables and are presented in Table 3. An ordinary concrete mix (C40) with a design compressive strength of 40 MPa fabricated with conventional Portland cement is used for the comparison.

2.3 Experimental tests

After curing in a natural environment, the concrete specimens were heated in a gas furnace, as shown in Fig. 2(a), following the time-temperature curve in accordance with ISO834. The compressive and splitting tensile strengths were measured by a 1000 kN universal testing machine. Pullout tests were performed using a 200 kN universal testing machine, as shown in Fig. 2(b). The loading rate was 1 mm/min, and the sampling frequency was 2 Hz. A dial indicator was attached to the free end of the specimen to measure the slip of rebar in concrete.

Provided that the specimen’s bond strength is relatively small, the distribution of the bond strength $\tau$ along the longitudinal direction is uniform; i.e., the ultimate bond strength is the average bond strengths as follows:

$$\tau = \frac{F}{u \times l} \quad (1)$$

where $\tau$ is the bond strength (MPa), $F$ is the pullout load(N), $u$ is the rebar circumference (mm) and $l$ is the rebar bonded length (mm).

The residual coefficient $\beta$ is defined as the ratio of the ultimate bond strength at $T \degree C$ ($\tau_T$) to the bond strength at room temperature ($\tau_c$), namely,

$$\beta = \frac{\tau_T}{\tau_c} \quad (2)$$

3. Experimental results

3.1 Observations

The heated specimens were naturally cooled to room temperature. The specimens exhibited different behaviors at various temperatures. At 200°C or room temperature, the specimens appeared dark gray and exhibited no apparent difference with each other; No thermal cracking or edge failure were found. When heated to 400°C, specimens displayed a light red color with no edge failure; however, thermal cracks developed. When subjected to 600°C, substantial thermal cracks developed in the specimen with a slightly larger number of wide cracks compared with the specimens exposed to 400°C; The specimen showed a dark red color with no edge failure. When the temperature was elevated to 800°C, the color of the specimen changed to a light gray color, the binder and coarse aggregates were damaged and absorbed moisture during the cooling process, which caused the specimen to expand, and thermal cracks rapidly developed. The specimen became loss and spalling occurred at the corners. And concrete failed where the concrete binder partially turned to black particulates (Fig. 3).

Scanning electron microscopy (SEM) was performed on the binder of the specimens after exposed to high temperatures. At room temperature, the results indicated that the binder of IPC was compact, and unreacted fly ash
(spherical shape) was observed. At 400°C, small cracks began to develop, but the total specimen was intact. At 600°C, the quantity and size of the cracks continued to develop with a reduction of the binder density. At 800°C, a significant change was observed in the binder, which revealed a large amount of voids. The binder was destroyed at this temperature.

### 3.2 Effect of mechanical strength

The specimens in Batch A were tested to evaluate the effect of mechanical strength on the bond performance between IPC and rebars after exposure to high temperatures. The results were listed in Table 4. The residual coefficients ($\beta$) in Table 4 suggest that the IPC specimens with higher strength exhibit a significant change in bond performance as the temperature increases, i.e., a greater increase in bond strength at 200°C and a significant reduction at temperatures of 400°C or higher compared with the IPC specimens with lower strength.

*Figure 5* displays the residual coefficients of the compressive strength, tensile strength, and ultimate bond strength as a function of temperature for the IPC specimens in IPC-14-2-75. The trends of the three types of strength appear to be consistent. At 400°C, splitting failure develops, and the mechanical performance decreases. A significant reduction of performance occurs at 600°C. Linear regression analysis of the experimental results provides a correlation coefficient of 0.813 for the ultimate bond strength with the compressive strength and a correlation coefficient of 0.902 for the ultimate bond strength with the splitting tensile strength. The regression results suggest that the three types of strength are positively related.
3.3 Effect of the relative protection layer thickness (c/d)

The failure mode of the specimens in Batch B after exposure to high temperature was the splitting and pullout failure. These specimens were tested to study the effect of the relative protection layer thickness on the bond performance between IPC and rebars after exposure to high temperatures. The experimental results are listed in Table 5. As the temperature increases, the specimens with larger rebar diameters and smaller relative protection layer thicknesses exhibit significant degradation in the bond strength between IPC and rebars after exposure to high temperatures. The thinner protection layer provides less protection of the bond at the contact surface between IPC and rebars at high temperatures and causes greater damage at failure compared with specimens that have a thicker protection layer. Therefore, the ultimate bond strength for specimens with a thin protection layer tends to rapidly degrade at high temperatures which is more significant as the temperature increases.

3.4 Effect of the bonded length

The specimens in Batch C were tested to analyze the effect of different bonded lengths on the bond performance between IPC and rebars at high temperature. The bond strength for each group of specimens after exposure to high temperatures is presented in Table 6. The residual coefficients β indicate that the reduction in the bond strength is similar for different bonded lengths for each temperature setting. Thus, the bonded length has a marginal effect on the degradation of the IPC-rebar bond performance at high temperatures. The bonded length affects the bond strength at room temperature.

The pullout tests indicate that the bonded length has a certain effect on the specimen's failure behavior. At room temperature and 200°C, splitting failure occurs in the specimens. At 400°C or higher temperatures, splitting failure occurs in specimens with a bonded length of 90 mm, whereas other specimens demonstrate splitting and pullout failure.
3.5 Comparison between IPC and ordinary concrete

Table 7 lists the experimental results of IPC specimens and ordinary concrete specimens. At room temperature, the bond strength of IPC with rebars is 45% higher than that of ordinary concrete with a similar compressive strength, which indicates that IPC has superior bond performance with rebars. After exposure to high temperatures, ordinary concrete exhibits faster and more significant degradation in the bond strength with rebars than IPC. Comparing the results between IPC and ordinary concrete, IPC attains a better bond than ordinary concrete for all temperature settings.

3.6 Fitted expression of the ultimate bond strength at high temperatures

The bond strength of rebars with IPC was examined considering the relationship of the bond strength with the compressive and tensile strengths, rebar characteristics and rebar bonded length. Based on the analytical expression for the bond strength between rebars and IPC developed for room temperature (Zhang et al. 2016), this paper proposes the following expression for the bond performance between IPC and rebars at high temperatures:

\[ \tau_1 = \left( -0.233 + 0.103 \times \frac{c}{d} \right) \times \frac{f_{cu}}{1 + 36.83 \times \left( \frac{T - 25}{1000} \right)^{1.794}} \]  

The calculated values based on (4) are primarily within the range of ±5% of the experimental results with few points over 15%. Figure 6 shows the experimental data and the fitted values in the same figure. The fitted curve is consistent with the actual values, and equation (4) adequately reflects the effect of temperature on the bond strength.

3.7 Two-segment bond-slip model

Some variables were observed in the bond strength and other factors that affect the ultimate bond strength. Based on the local bond-slip model for rebars in recycled concrete in the literature (Xiao and Falkner 2007), the bond strength (\( \tau \)) and the relative slip (\( s \)) between rebars and IPC are described by the local bond-slip relationship in (5), which is composed of an ascending branch and a descending branch.

\[ \tau = \begin{cases} \left( \frac{\bar{\tau}}{\bar{s}} \right) \chi \frac{b(\bar{\tau}-1)^2}{\bar{\tau}} & \bar{\tau} \leq 1 \text{ (ascending branch)} \\ \frac{\bar{\tau}}{\bar{s}} \chi \frac{25}{\bar{\tau}} & \bar{\tau} > 1 \text{ (descending branch)} \end{cases} \]  

Where \( \bar{\tau} \) is the peak temperature, \( \tau_1 \) is the ultimate bond strength, \( c/d \) is the relative protection layer thickness (\( c \) is the protection layer thickness, and \( d \) is the rebar diameter), \( L_0 \) is the bonded length, \( f_{cu} \) is the compressive strength of IPC cubes and \( A, B, C, D, E, F \) are coefficients. By best fitting the relationship between IPC and rebars at high temperatures:

\[ \tau_1 = \left( A + B \times \frac{c}{d} \right) \times \left( C + D \times \frac{d}{L_0} \right) \times \frac{f_{cu}}{1 + E \times \left( \frac{T - 25}{1000} \right)} \]  

Note: splitting and pullout failure occurs in ordinary concrete specimens.
mm for rebar diameters of 10, 14 and 18 mm. Considering the effect of rebar spacing and temperature on the slip, the expression for the local slip at bond failure can be written as

\[ s_1 = G \times l \left[ H \left( \frac{T}{1000} \right)^2 + I \left( \frac{T}{1000} \right) + J \right] \]

where \(G, H, I, J\) are coefficients, \(T\) is the target temperature and \(l\) is the rebar spacing. The fitted expression of \(s_1\) is

\[ s_1 = 0.095 \times l \left[ 2.99 \left( \frac{T}{1000} \right)^2 - 0.7 \left( \frac{T}{1000} \right) + 0.9994 \right] \]

Figure 7 shows the bond-slip curves for different specimens at 600°C. The bond-slip curves for specimens in IPC-14-1-75 at different temperatures are shown in Fig. 8.

As shown in Figs. 7 and 8, the ascending branch of the bond-slip curves is similar for different temperatures because the parameter \(a\) in (5) is a constant. The descending branch of the curve varies with temperature and parameter \(b\).

By grouping the test results and best fitting the expression with the experimental results, parameter \(a=0.6\). The fitted values of parameter \(b\) (Table 9) are dependent on the temperature.

As the temperature increases, \(b\) increases, followed by a decrease, and subsequently increases. If the specimen is heated to 200°C, the descending branch of the bond-slip curve is relatively steep. If the specimen is heated to 600°C, the descending curve is relatively smooth and gradual. Parameter \(b\) increased at 800°C. High temperatures can significantly weaken the bond performance between IPC and rebars, which causes a rapid reduction of the bond strength at failure. Through cubic curve fitting, the expression of parameter \(b\) with temperature \(T\)

| Group  | 25°C | 200°C | 400°C | 600°C | 800°C |
|--------|------|-------|-------|-------|-------|
| 1      | 0.80 | 0.78  | 1.02  | 1.36  | 1.83  |
| 2      | 0.82 | 0.75  | 1.05  | 1.30  | 1.96  |
| 3      | 0.80 | 0.79  | 1.05  | 1.31  | 1.90  |
| 4      | 0.92 | 0.90  | 1.13  | 1.49  | 2.08  |
| 5      | 0.61 | 0.54  | 0.78  | 1.03  | 1.55  |
| 6      | 0.78 | 0.75  | 1.01  | 1.28  | 1.95  |
| 7      | 0.81 | 0.78  | 1.11  | 1.34  | 1.88  |
is obtained as follow:

\[
b = 22 \left( \frac{T}{1000} \right)^3 - 24 \left( \frac{T}{1000} \right)^2 + 4 \frac{T}{1000} + 2.8
\]

(8)

The local bond-slip relationship for rebars in IPC after exposure to high temperatures can be expressed as

\[
\frac{b}{s} = \begin{cases} 
\frac{\left( \frac{\tau}{\tau_1} \right)^{0.6}}{b(s-1) + s} & \tau \leq \tau_1 \text{(ascending branch)} \\
\frac{\left( \frac{\tau}{\tau_1} \right)^{0.6}}{b(s-1) + s} & \tau > \tau_1 \text{(descending branch)} 
\end{cases}
\]

(9)

(10)

(11)

where \( b, \tau_1 \) and \( s_1 \) are given by equations (8), (4) and (7).

Figure 9 compares the fitted curves with the test curves. Figure 9(a) shows the splitting failure of specimens in IPC-14-2-60 at room temperature. Figure 9(b) shows the splitting pullout failure of specimens in IPC-18-2-75 at 400°C. Figure 9(c) presents the splitting pullout failure of specimens in IPC-10-2-75 at 600°C. Figure 9(d) gives the splitting pullout failure of specimens in IPC-14-2-75 at 800°C. Expression (9) reasonably describes the local bond-slip relationship and can be employed for analyzing the bond and slip between IPC and rebars at high temperatures.

4. Conclusion

Laboratory tests have been performed to evaluate the effect of the compressive and tensile strengths, relative protection layer thickness and bonded length on the reduction of the bond strength between IPC and rebars after exposure to high temperatures. A regression analysis has been performed using the experimental results. Based on the study, the following major conclusions are formed:

1) IPC shows a better bond with rebars than ordinary concrete at high temperatures.
2) The degradation behavior of the bond strength between IPC and rebars is similar to the reduction behavior of the compressive and tensile strengths at high temperatures. A thinner protection layer appears to cause a significant reduction in the bond performance. The bonded length of rebars contributes to bond degradation at room temperature but does not contribute at high temperatures.
3) The fitted expression of the bond strength between IPC and rebars at high temperature and the local bond-slip model provide theoretical contributions to engineering practice.

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| Temperature | 25°C | 200°C | 400°C | 600°C | 800°C |
|-------------|------|-------|-------|-------|-------|
| \( b \)     | 2.82 | 2.95  | 1.81  | 1.58  | 2.16  |

Table 9 Parameter \( b \) for different temperatures.
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Fig. 9 Comparison of fitted curves and test curves.