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Modeling the effect of high temperature on the bond of FRP reinforcing bars to concrete

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Abstract

The effect of high temperature on the bond between fiber reinforced polymers (FRP) reinforcing bars (rebars) and concrete was studied. The bond strength exhibited a severe reduction of 80–90% at relatively low temperature (up to 200°C), accompanied by changes in the pullout load-slip behavior. A semi-empirical model was developed in order to describe the extent of reduction in the bond strength as the temperature rises. The model is based on the following parameters: glass transition temperature of the polymer layer at the surface of the rod; polymer's degree of crosslinking; the residual bond strength at high temperature after the polymer of the external layer of the rebar ceased to contribute to the bond. The parameters of the rods that were tested for pullout at various temperatures were introduced into the model. The output curves of bond–temperature relationships showed good agreement with the test results. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: FRP; Concrete; High temperature

1. Introduction

Fiber reinforced polymers (FRP) attracted much attention as a form of concrete reinforcement in the past decade. FRP exhibits good corrosion resistance and is electromagnetically transparent. Thus it can be used in places where steel cannot be used, either because it might be exposed to aggressive environment or it may cause electromagnetic interference. Two major uses of concrete reinforcement are known: (i) internal reinforcement, similar to ordinary steel reinforcement [1,2] and (ii) external reinforcing layers over concrete members for repair and strengthening purposes [3,4].

In the first use, the FRP rods are embedded in the concrete and it appears that besides chemical attack by the aggressive environment of the concrete and some external influences, such as chlorides, the rods are free of other effects. Thus most of the studies on the durability of FRP rebars concentrated on the effect of the above environments on the properties of the rods [5–7]. However, not much attention was given to the behavior of the FRP rods subjected to high temperature.

At high temperature, above the glass transition temperature (T_g), the polymer loses its mechanical properties, depending on the amount of crosslinks and degree of crystallization [8]. In FRP, however, the inorganic fibers support the load in the longitudinal direction. The properties in this direction depend mainly on the properties of the fibers, which exhibit better thermal properties than the resin. Kumahara et al. [9], for example, found a reduction of approximately 20% in the tensile strength of glass and carbon FRP rods at a temperature of 250°C, which was much above the T_g of the resin.

When other properties of a unidirectional FRP element were tested, such as flexural strength, which is affected by the transfer of shear stresses through the matrix, a significant reduction in the strength was seen at high temperature [10].

The bond of FRP to concrete in untreated rods is relatively low. Therefore a special treatment is usually given to the surface of the rods by several organic and inorganic means (sand coating, helical wrapping with additional fibers, molded deformations, etc.). Yet, the polymer matrix has an important role in the stress transfer between the rod and the concrete. It might be expected that the bond to concrete would be the first to be damaged when the temperature rises. Such a damage to the bond was reported by Katz et al. [11,12]. In the

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present paper, the results from pullout tests carried out at high temperatures are presented and a semi-empirical model to account for the effect of temperature on the bond is developed.

2. Experimental

Pullout tests of glass fiber reinforced polymers (GFRP) at high temperature were conducted. Four types of rods were tested, each representing a different bond mechanism to the concrete. Fig. 1 presents the rods and their surface and Fig. 2 presents their exposed fibers after burning off the polymer that binds and covers the fibers.

1. Rod CB has molded deformations on the surface, similar to ordinary deformed steel rebars. The surface of the rod between the deformations was smooth and the bond relies mainly on the shear strength of the deformations. The polymer at the surface is a urethane modified vinyl-ester and the polymer at the core of the rod was recycled polyethlene terephthalate (PET).
2. Rod CPH contains wraps of helical braid of fibers on the surface and with additional fine sand particles embedded evenly on the surface. The polymer was vinyl-ester throughout the rod.
3. Rod CPI contains wraps of a wide braid of fibers on the surface. Additional roughness was achieved through excess of polymer on the surface which "froze" in an irregular manner on the surface after polymerization. The polymer was vinyl-ester throughout the rod.
4. Rod NG has tight wraps of a narrow braid of fibers which produced large deformations in the rod. A thick layer of polymer (which was somewhat sticky and soft) covered the rod and sand particles were embedded unevenly on its surface. The thick layer of polymer partly hid the deformations. A small gap of 1–2 mm was found between the rod and the surrounding concrete after concrete curing, which separated between the rod and the concrete. The polymer of the core was assumed to be polyester and an unknown type of polymer composed the surface layer (data was not provided).

Ordinary rebar of deformed steel of the same diameter (ST) was used for comparison and for resolving the particular parameters of the FRP rebars relative to the ordinary steel used today.

The thermal properties of the polymer from the surface of the rods were analyzed using differential scanning calorimeter (DSC) in order to determine the glass transition temperature (T_g) of the polymer and to estimate the extent of crosslinks, Cr. Tests were carried out according to ASTM D3418 and D5028. The results are presented in Table 1.

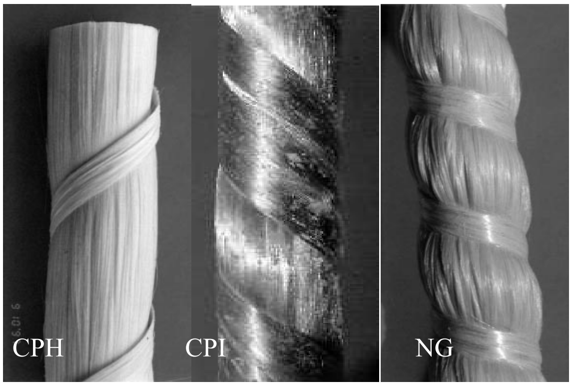

Fig. 2. Exposed fibers of tested rods after burning off the polymer.

Table 1
Properties of the polymer at the surface of the rods[a]

Rod type	T_g (°C)	Cr (%)
CB	124	75
CPH	122	90
CPI	98	95
NG	55	60

[a] T_g – glass transition temperature, Cr – degree of cross linking.

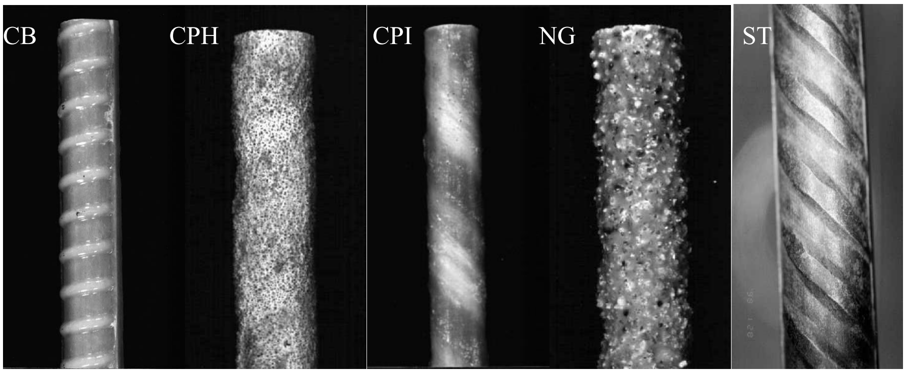

Fig. 1. Images of the tested rebars.

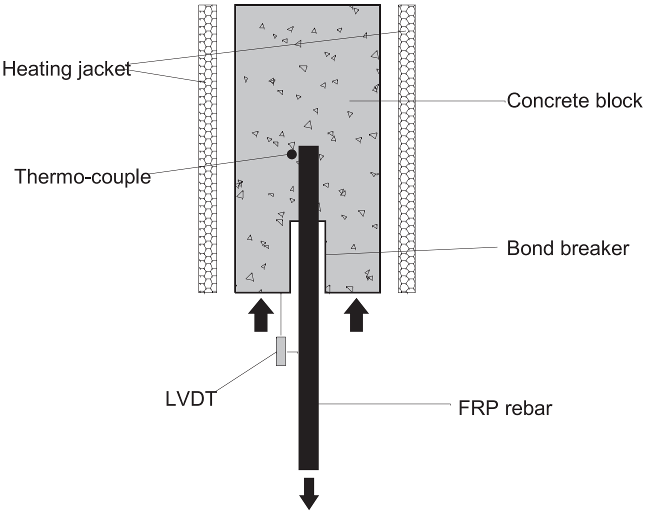

Fig. 3. Pullout test setup during heating.

All the tested rods were #4 rebars (12.7 mm diameter). The rod was embedded vertically in a concrete cylinder (150 mm diameter and 300 mm long). Embedded length (*l*) was 63 mm (5 diameters) following a bond breaker zone of 63 mm, in accordance with FILEM/FIP recommendation RC6 (1978). A special heating jacket wrapped the concrete cylinder to allow heating of the specimen while it is mounted on the testing machine (see Fig. 3). The temperature close to the rod, in the center of the concrete was monitored continuously by a thermocouple and pullout was performed when the temperature reached the testing temperature.

The complete curve of pullout load vs. loaded end slip (P–s) was recorded in order to analyze changes in the P–s behavior due to the effect of temperature. The average bond strength was determined by dividing the maximum pullout load ($P_{\max}$) by the embedded surface, assuming a uniform bond stress distribution along the rod (Eq. (1)).

$$\tau = \frac{P_{\max}}{\pi d l}, \qquad (1)$$

where $P_{\max}$ is the peak load, d the rod's diameter, and l is the embedded length.

3. Results

3.1. Pullout load-slip behavior

A reduction in the peak pullout load was seen for all the rods as the temperature increased (see Table 2 and Fig. 4). The reduction was accompanied by increased pre-peak deformation and a change in the post-peak behavior.

Behavior at room temperature: At room temperature the average bond of the FRP rebars was as high as the steel rebar, apart from the NG rod in which lower bond strength was observed. The lower bond strength of this type of rod is probably a result of the gap between the rod and the surrounding concrete described before.

Post-peak slip-weakening behavior was observed in all the rods at room temperature (Fig. 4(a)). This behavior characterizes a progressive destruction of the

Table 2
Bond strength at room temperature and the residual bond at 200°C

Rod type	R.T. (20°C)		~130°C		~200°C		
	Peak load (kN)	Average bond (MPa)	Peak load (kN)	Average bond (MPa)	Peak load (kN)	Average bond (MPa)	Residual (%)
CB	31.3	13.2	16.0	6.7	2.6	1.1	8.3
CPH	29.0	12.2	16.0	5.0	3.8	1.7	13.9
CPI	25.6	10.9	11.9	6.7	4.0	1.6	14.7
NG	9.7	4.1	1.8	0.8	1.9	0.8	19.5
STEEL	25.2	10.6	19.3	8.1	16.4	6.9	67.0

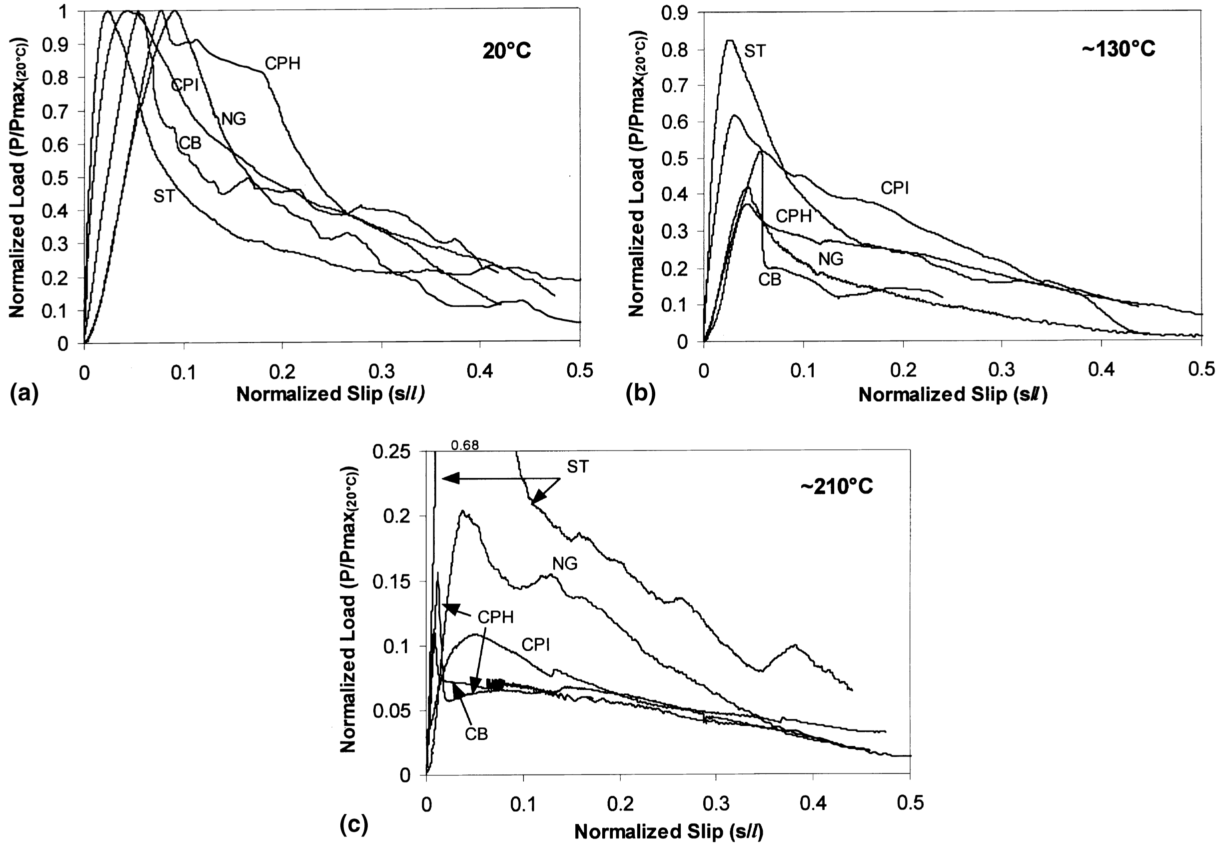

Fig. 4. Pullout load-slip (P–s) behavior at various temperatures.

surface of the rod or of the surrounding concrete during slippage of the rod, leading to a relatively rapid reduction of the loads after attaining the peak load. For the steel rebar, the damage is solely located in the surrounding concrete at all temperatures while the damage in the FRP rebars at 20°C was located in both rod's surface and concrete for the rods with good external properties and fine roughening (CPH, CPI). The rods with large deformations (CB) or weak external layer (NG) failed only in their external layer without damaging the concrete. As a result, a rapid reduction in the pullout load was characterized for rods ST, CB and NG after the peak load was attained. For rods CPI and CPH, a gradual reduction of the loads was observed for a short slipping distance after the peak (mainly for CPH) followed by a rapid reduction. In all cases a negligible pullout load was observed (10–20% of the maximum load) after a slip of 0.5 of the embedment length (Fig. 4(a)).

Behavior at temperature of 130°C: As the temperature was raised to approximately 130°C, a reduction in the peak load was seen for all the rods, being approximately 20% for the steel rods and 40–60% for the FRP rods (Fig. 4(b)).

In addition to the reduction in the peak loads the post-peak behavior shifted towards a pure friction post-peak behavior (a continuous linear reduction of the post-peak loads). The degree of changes in the FRP rods depends on the properties of the bonding system, mainly the properties of the polymer in the external layer of the rods. The behavior of the CB rods was of exception at that temperature, and it exhibited similar behavior as in room temperature (i.e., a significant reduction in the pullout loads after the peak rather than a linear reduction as for the others), probably due to its higher T_g (Table 1).

Behavior at temperature of 210°C: At a higher temperature (~210°C) the FRP rods lost most of their initial bearing capacity and values of 10–20% of the initial peak values were observed (Fig. 4(c)). At that temperature the P–s behavior is mainly affected by the inorganic component of the bonding system at the outer surface of the rod, thus exhibiting some initial slip resistance as was seen for CB and CPH, or linear reduction for CPI and NG. Of special interest is the latter, as it maintained the highest maximum load (20% of the maximum load at room temperature) due to its special structure, that obtained by deformations of the longitudinal fibers (Fig. 2). This structure is supposed to support the bond also in temperatures above the T_g, when the polymeric cover stops from functioning.

However, the thick external layer of polymer covering the core of the NG rods (1–2 mm) prevented a beneficial use of the special structure at all temperatures and the absolute values of bond and loads were low (see Table 2).

3.2. Pre-peak behavior

The pre-peak behavior was characterized by the slope of the ascending branch of the pullout load-slip curve. Decrease in the pre-peak slope represents softening of the bonding system accompanied by increased deformation before reaching the peak load, thus providing with some warning before a catastrophic failure occurs. The reduction of the slope was approximately 50% of the value at room temperature for all the tested rods (see Fig. 5), despite of the different properties of the rods (various types of FRP rebars or steel rebars).

A massive escape of water vapor was observed through the interface between the rebar and the concrete, which led to a reduction in the adhesion between them and to an internal pressure that was superimposed on the external pullout load. It is possible that the decrease in the slope of the curves is mainly a result of the increased vapor pressure that led to larger pullout slip for a given external load.

3.3. Average bond strength

The results, shown in Fig. 6 and Table 2, indicated that bond strength of FRP rods at room temperature is relatively high in most of the cases. As the temperature increases to approximately 80–120°C a reduction in the bond can be seen. In some cases rapid reduction occurred for a small temperature rise while in other cases the rate of reduction was relatively moderate, as can be seen in Fig. 6.

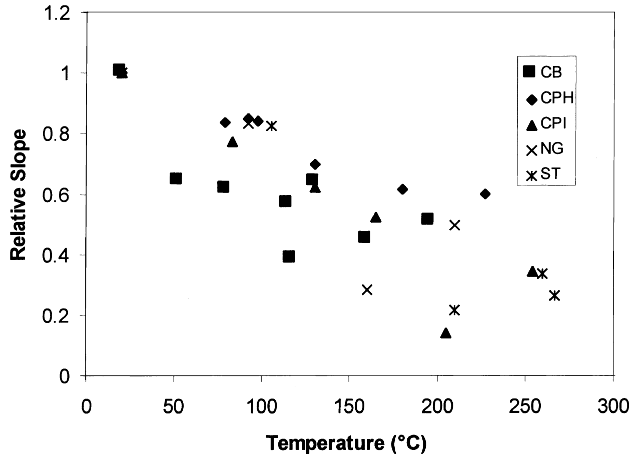

Fig. 5. Effect of temperature on the slope of the ascending branch of the P–s curves (relative to 20°C).

At temperatures above 200°C a constant bond strength was seen which will be referred to as the residual strength, τ_r. It should be noted that the maximum temperature tested here was 200–250°C. The bond strength at various temperatures and the residual bond relative to the bond at room temperature are listed in Table 2.

A continuous reduction in the bond strength of the steel rebar was seen as the temperature increased (see Fig. 6). In the tested range of temperatures the reduction was of approximately 33%, similar to the results reported by Diederichs and Schneidwe [13].

The effect of water vapor escape through the concrete–rod interface can explain the reduction in the pullout load seen for the steel rebar. However, additional reduction was seen for the FRP rebars at temperatures lower than the boiling temperature, which is attributed to the changes in the properties of the bonding system of each rod (see detailed discussion in the following chapters).

4. Bonding mechanisms and their sensitivity to temperature

A significant reduction in the peak pullout load (representing also the average bond strength) was seen for all the FRP rods, starting at a temperature of 80–130°C. This temperature was found to be approximately the glass transition temperature of the polymers at the surface of the rods (Table 1).

The following bonding mechanisms are used to improve the bond of the FRP rebars to the concrete; in all of them the polymer at the surface of the rod plays a significant role:

1. Large deformations, which give the rod an appearance similar to that of deformed steel rebars (CB in Fig. 1).
2. Winding a braid of fibers around the core. The winding can be either loose, protruding over the surface of the rod (CPH and CPI in Fig. 2), or tight, leading to dents beneath the helix and humps between the windings (NG in Fig. 2).
3. Roughening of the surface by embedding sand particles in the resin over the surface (CPH and NG in Fig. 1) or by using excess of polymer during manufacturing (CPI in Fig. 1). The excess polymer of the latter remains unprocessed on the surface, leaving the rod with rough surface after polymerization of the resin.

The polymer used for the production of FRP rebars is a thermosetting resin, usually unsaturated polyester, vinyl-ester, epoxy or urethane modified vinyl-ester and epoxy. Unsaturated polyester, which is the most economical resin used in various FRP applications, is

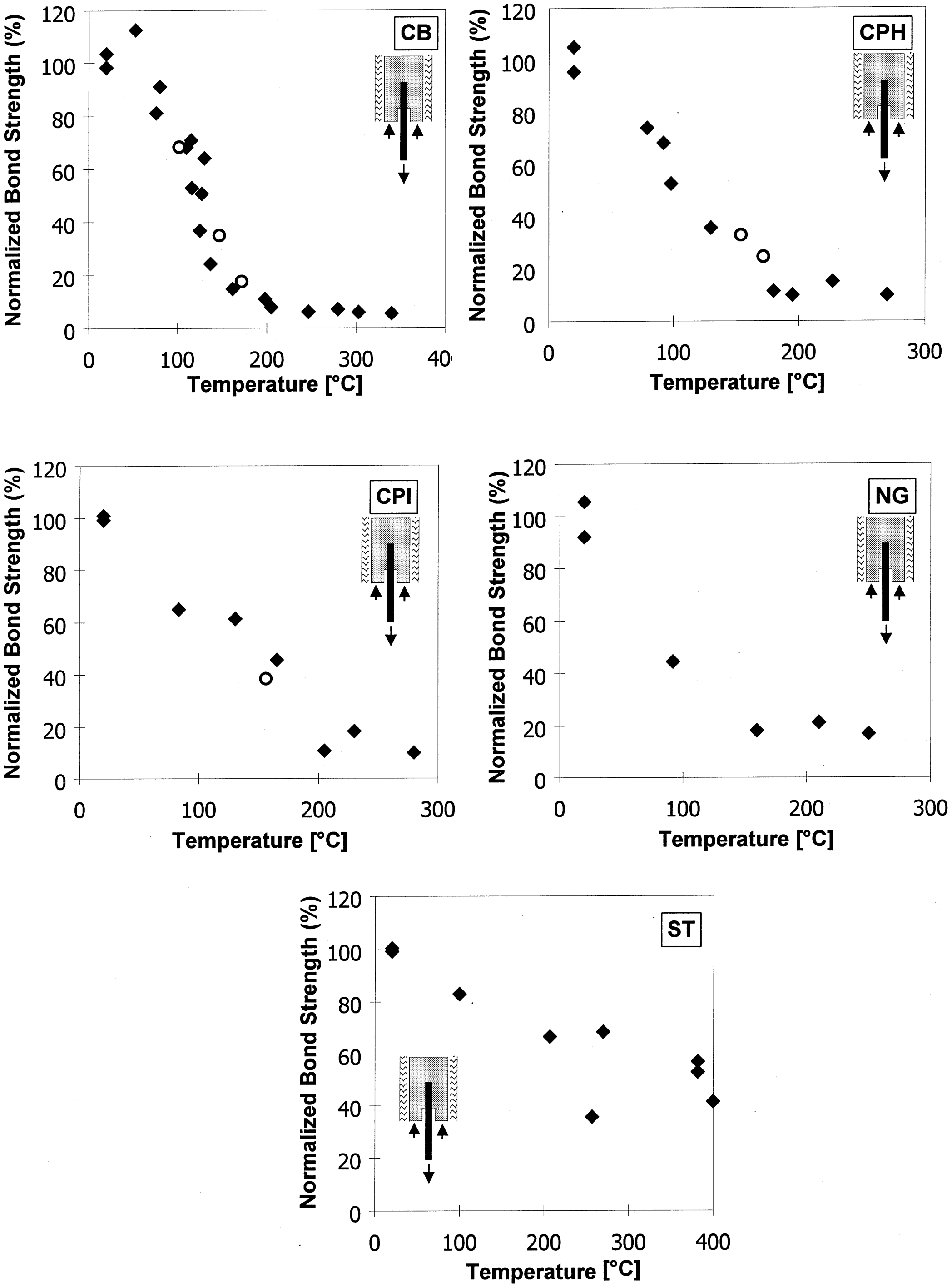

Fig. 6. Effect of temperature on the normalized bond strength (relative to the bond at room temperature) of various FRP rods.

sensitive to the alkaline environment of the concrete [5,6] and modified resins are commonly used either at the surface of the rod or also in the core.

However, a reduction in the mechanical properties of the polymer is known to occur at the glass transition temperature (T_g). The effect of T_g on the reduction in the mechanical properties of the polymer is not uniform for all types of polymer [8]. For truly thermoplastic polymers the material softens significantly at a temperature above the T_g and loses its mechanical properties. When cross-links are present, as in thermosetting polymers, the reduction in the mechanical properties with temperature rise is more gradual, although a significant reduction in the mechanical properties can still be identified at T_g.

In the longitudinal direction, the properties of the rod are mainly affected by the properties of the reinforcing fibers (i.e. glass, in this study) that are not affected by the temperature at the tested range. According to Li et al. [15] the P–s relationships of the ascending curve are related to the longitudinal properties of the rod. Therefore the reduction of the slope of the ascending curves as the temperature rises is mainly attributed to the vapor pressure effect that was seen also for the steel rebar rather than to the change in the properties of the polymer.

Based on the previous discussion and the results seen in Fig. 6, it can be assumed that the bond strength of FRP rebars to concrete relies mainly on parameters that are related to the surface properties and geometry. Four parameters were identified, affecting the bond as the temperature rises:

1. *Bond strength at room temperature*: This parameter is a function of the geometry of the surface (wrapping with helical braid around the core, embedment of sand, formation of deformations, etc.) and the quality of the polymer at the surface. Detailed study on the parameters affecting the bond strength at room temperature are reported by Katz [14].
2. *T_g of the polymer at the surface of the rod*: As discussed earlier, at this temperature the polymer changes from a strong and rigid solid to a soft and weak one. Below that temperature the bond strength is similar to the value at room temperature and above it the bond is reduced to a residual value, which will be discussed later. The reduction is not sudden but extends over a range of temperatures, depending on the other properties of the polymer.Some reduction in the bond strength was seen, however, for steel reinforcement at relatively low temperature, which for some polymers, was below the T_g (Fig. 4). This reduction was attributed by Katz et al. [11] to changes in the properties of the concrete and flow of steam through the interface between the rod and the concrete at temperature close to the boiling temperature of the water in the concrete pores. It might be assumed that in cases of polymers with a T_g which is higher than the boiling temperature noted above, some reduction in the bond will be seen at temperatures lower than the T_g, as was observed for the steel. At higher temperatures the loss of bond is attributed to the loss of mechanical properties of the polymer only, regardless of the changes in the concrete. For polymers of low T_g (below ~80°C) the reduction will begin at the T_g, as the polymer becomes weaker and softer before any change in the concrete occurs.
3. *Degree of crosslinking* (*Cr*): Crosslinks between the chains of polymer turn the polymer from thermoplastic into a thermosetting one. As the amount of crosslinks increases the polymer becomes more thermosetting in nature, and the reduction in the mechanical properties is moderated. Thus it is expected that a reduction in the bond strength with temperature, which in turn relies on the properties of the polymer, will be more moderate as the amount of crosslinks increases.
4. *Residual bond strength τ_r*: The residual bond strength is the bond strength at a high temperature ($\leqslant 350°C$), where no additional reduction is present. As can be seen in Fig. 6, the bond strength of FRP rebars remains constant at temperatures above 200°C. It is possible that additional reduction can take place at much higher temperatures associated with further destruction of the fibers. However, this range is not realistic for practical purposes. At high temperatures the contribution of the polymer to the bond strength becomes negligible and it is mainly the inorganic system, which provides the residual bond strength. The inorganic system can be helical fibers wrapped around the core, sand particles embedded on the surface but also deeply into the core, or large deformations formed by the longitudinal fibers. It should be noted that if the deformations of the longitudinal fibers are formed by the resin, it is the polymer which keeps this shape and high temperature can destroy this mechanism. Braided rod may have a better residual bond, as interweaving of the fibers is less dependent on the polymer.

Summarizing these effects, the behavior of bond strength by the effect of temperature can be described schematically as two plateaus one of relatively high bond values (τ_0), below the T_g; and the other, having relatively low bond values (τ_r), at temperature above the T_g. The temperature at which the reduction occurs and the degree of reduction depend on the T_g and degree of crosslinking, respectively.

5. Modeling the effect of temperature on the bond strength

The proposed model that describes the effect of temperature on the average bond strength is a semi-empirical one. The general form of the equation was determined in order to follow the trends presented in Fig. 6. However, almost all the constants in the model represent actual material properties. An equation of the form $y = \tanh(-x)$ was chosen to describe the effect of temperature on the bond strength discussed above. The basic configuration of the equation is presented by the solid line in Fig. 7. The equation has two asymptotes at $y = -1$ and $y = 1$ connected by an inclined curve passing through the origin. The modified equation, which takes into account the physical properties of the rod, is described in Eq. (2).

$$y = a \tanh[-b(x - k_1 c)] + d, \tag{2}$$

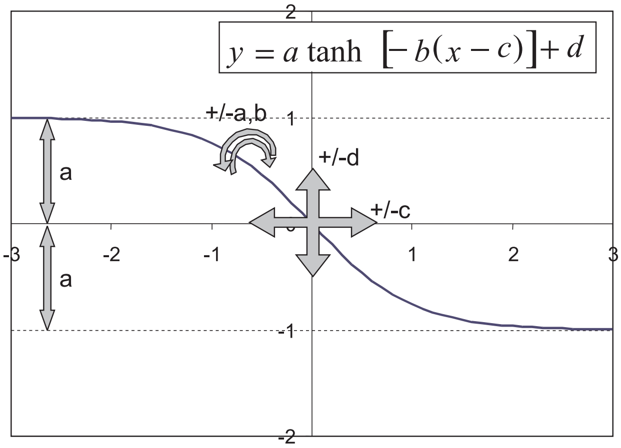

Fig. 7. Schematic presentation of the proposed model.

where a, b, c, d and k_1 are coefficients related to the properties of the rods, as will be described in the following, y represents the normalized bond strength τ^*, and x represents the temperature, T. The asterisk in the followings denotes values of bond strength normalized to the values at room temperature.

6. Parametric analysis

The parametric analysis was carried out by correlating the coefficients from Eq. (2) with actual materials properties, based on the results shown in Fig. 6.

a and *d* – the parameters govern the vertical location of the curve on the y-axis. Assuming that the bond strength remains constant up to a temperature approaching the glass transition temperature ($\tau_0^* = 1$), then:

$$\tau_r^* + \Delta\tau^* = 1, \tag{3}$$

where $\Delta\tau^*$ is the magnitude of bond loss, and τ_r^* is the normalized residual bond.

According to the definition in Eq. (2), as seen also in Fig. 7

$$a = 0.5\Delta\tau^*. \tag{4}$$

Introducing Eq. (3) in Eq. (4) provides the following expression for a

$$a = 0.5(1 - \tau_\mathrm{r}^*). \tag{5}$$

For large values of x, Eq. (2) gets the value $(-a + d)$ thus

$$-a + d = \tau_\mathrm{r}^*. \tag{6}$$

Introducing Eq. (5) in Eq. (6) yields the final expression for d

$$d = 0.5(1 + \tau_\mathrm{r}^*). \tag{7}$$

b and *c* – the coefficients b and c govern the location on the horizontal axis where the transition from the upper to the lower asymptote takes place. Two physical properties govern the behavior in this zone and its location: the extent of crosslinks (Cr) and the glass transition temperature (T_g), as discussed before. It was assumed that the slope of the curve at the transition zone is related to the extent of crosslinks and the temperature at which the reduction in the bond begins is related to the T_g. For polymers having low T_g, it was defined at the intersection between the tangent at the centerline and the horizontal line at $y = 1$ (see line $T_{\mathrm{g}_{(1)}}$ in Fig. 8).

Using the derivation at the center-point ($y'_{(x=k_1 c)} = -ab$) and a and b from Eqs. (5) and (7) yields the following expression for c

$$c = T_\mathrm{g} + \frac{k_1}{b}. \tag{8}$$

As was discussed before, some reduction in the bond strength was observed for the steel rods at a relatively low temperature, which was below the T_g of some polymers and above it for others. The coefficient k_1 accounts for this effect. For polymers having low T_g, the reduction in bond strength, identified for the steel, does not affect the bond strength of these rods, as the bond relies on the properties of the polymer only, which loses its strength at relatively low temperatures. Thus, k_1 gets the value of 1 to take into account the full effect of bond reduction at T_g, described in Eq. (8) (see $T_{\mathrm{g}_{(1)}}$ in Fig. 8). For polymers having a high T_g, some reduction in the bond strength can be seen already prior to T_g, similar to the reduction in steel rods in this range of temperature. Therefore, it was assumed for these polymers that T_g represents the bond strength at the center point, marked as $T_{\mathrm{g}_{(2)}}$ in Fig. 8, and $k_1 = 0$ for these cases. The value of k_1 decreases gradually from 1 to zero, as T_g rises gradually from approximately 80–120°C. However, further study of the bond strength in this range of temperatures

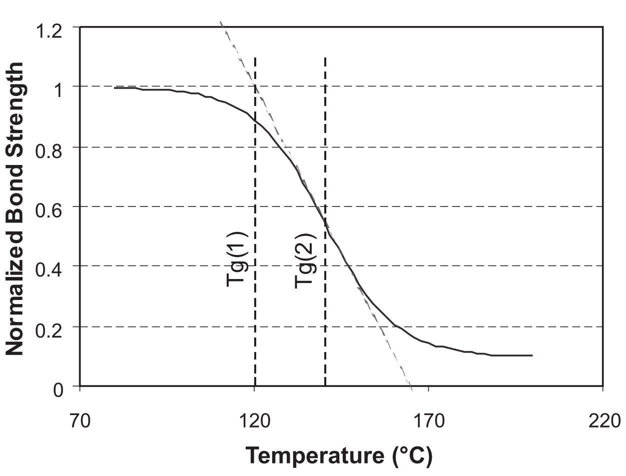

Fig. 8. Defining T_g in the numerical model.

is needed, in order to establish a more accurate relationship. A linear reduction was assumed here.

The coefficient b is the only parameter that could not be directly related to a physical property, but indirectly it is inversely proportional to the degree of crosslinking, Cr, of the polymer (see Eq. (9)). It must be determined experimentally by best fit of test results with the polymer datum. A value of 0.02 was found to fit k_2 for all the tested rods, regardless of the type of polymer.

$$b = \left(\frac{k_2}{\mathrm{Cr}}\right). \tag{9}$$

Introducing all the expressions for a, b, c, d, k_1 and k_2 into Eq. (2) yields the overall expression for the normalized bond strength, τ^* (Eq. (10)) taking into account the effect of temperature, T, and rod's properties (the normalized residual bond strength, τ^*_r, degree of crosslinking, Cr, and glass transition temperature of the polymer at the surface of the rod, T_g

$$\begin{aligned}\tau^* = {} & 0.5\left(1 - \tau^*_r\right) \tanh\left\{ -\frac{0.02}{\mathrm{Cr}}\left[T - k_1\left(T_\mathrm{g} + \frac{k_1}{0.02}\mathrm{Cr}\right)\right]\right\} \\ & + 0.5\left(1 + \tau^*_\mathrm{r}\right),\end{aligned} \tag{10}$$

where

$$k_1 = \left\{\begin{array}{ll} 1, & T_\mathrm{g} \leqslant 80, \\ 1 - 0.025(T_\mathrm{g} - 80), & 80 < T_\mathrm{g} < 120, \\ 0, & T_\mathrm{g} \geqslant 120. \end{array}\right\}.$$

7. Comparison with test results

The values of the coefficient k_1 were estimated as described earlier, as a function of T_g. Curves from the model were compared with the test results shown before in Fig. 6, and the comparison is presented in Fig. 9. Adequate agreement between the numerical model and the test results can be seen despite the different proper-

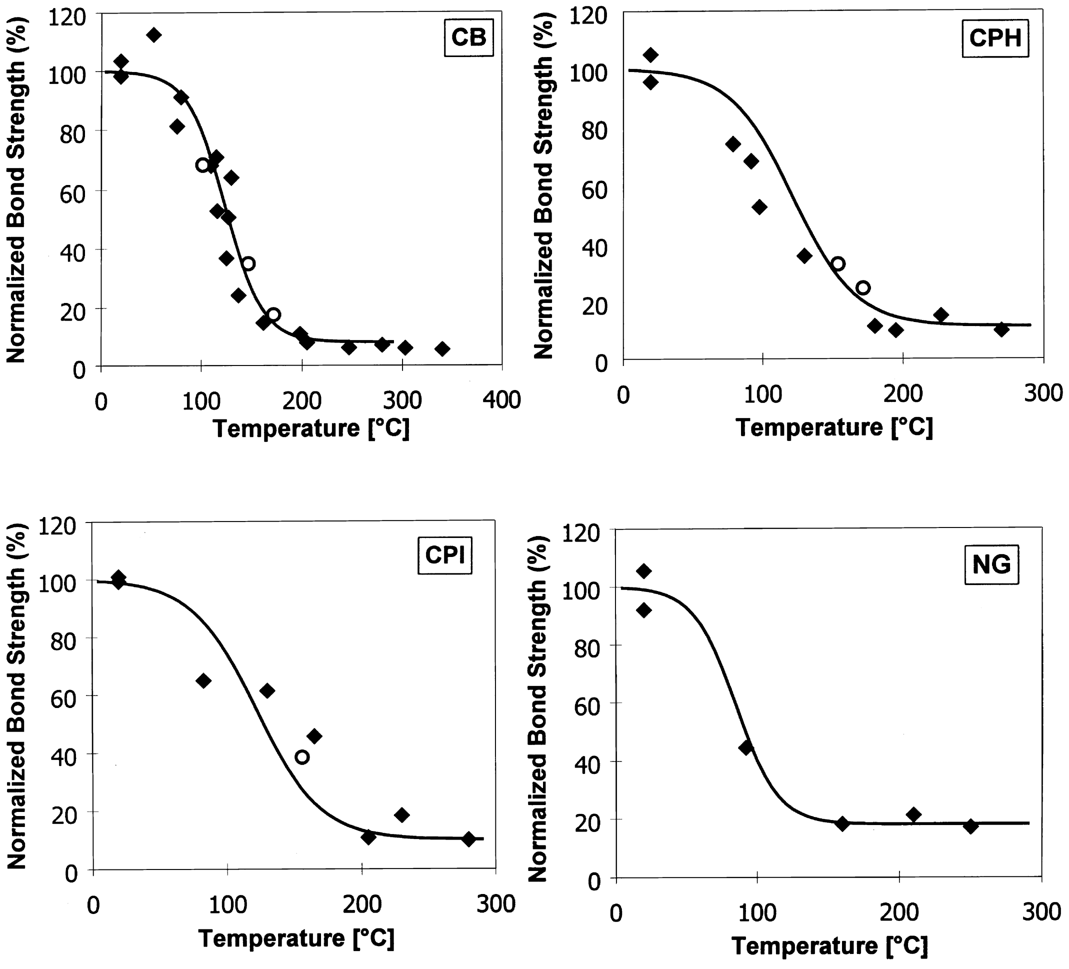

Fig. 9. Comparison of predicted and experimental results.

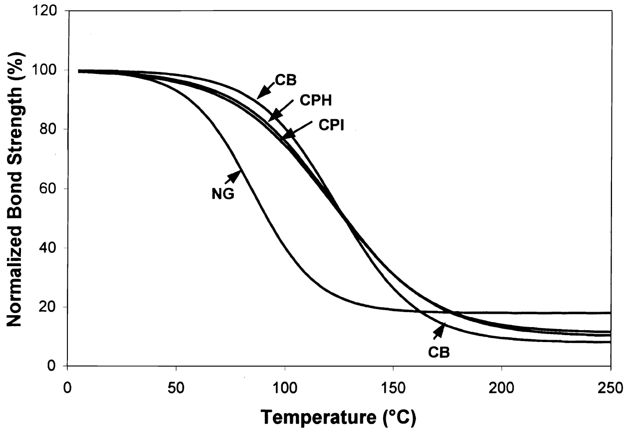

Fig. 10. Comparison of the effect of temperature on the bond of different rods.

ties of the rods, their materials and their external structure.

In order to compare between the behavior of the different rods, the characteristic normalized curves of bond strength vs. temperature were plotted together (Fig. 10). Early reduction in the bond strength is seen for the NG rod, which reflects its low T_g.

The residual bond, however, is relatively high, representing the effect of the inorganic components supporting the bond at higher temperature (sand particles and tight wrapping of the helix). For the CPH and CPI rods, the gradient of bond loss is relatively moderate, and they both have approximately the same residual bond, despite the sand particles embedded in the CPH rods.

For the CB rod, the reduction is at a higher temperature. This reflects its higher T_g. However, the gradient of bond loss is steeper, and the residual bond is the smallest, indicating that the bond relies mainly on the polymeric system.

It is possible to conclude from the above that improving one or some of the followings can modify the bond at high temperature: (i) Use of a polymer with high T_g in order to increase the temperature at which the reduction in bond begins. (ii) Use of a polymer with a high extent of crosslinks to moderate the gradient of bond loss. (iii) Improvement of the inorganic system, which supports the bond at a high temperature where the polymer practically ceases to contribute to the bond.

8. Conclusions

Results from tests on the effect of temperature on the bond strength of FRP rods to concrete indicated a severe reduction in the bond strength as the temperature rises. The bond values obtained for the FRP rebars at room temperature were comparable with those obtained for the steel rebars. However, the bond reduces approximately to 10% of its initial value at temperature in the range of 150–200°C, while a reduction of only ~30% was seen for the steel at the same temperature range. The reduction occurred at approximately the T_g of the polymer at the surface of the rods and it was steeper for polymers having a lower degree of crosslinking.

A semi-empirical model was developed to simulate this effect. The model is based on a hyperbolic tangent equation that follows the reduction in the bond strength. The constants of the equation are based on the physical properties of the rod and of the resin in its surface, thus enabling one to predict the bond properties at high temperature of a new rebar composition.

Three parameters were found to control the behavior of the bond strength at high temperatures:

1. The residual bond at high temperature, τ_r^* which is related to the inorganic components of the bond system. The inorganic components provide the bond after the resin that provides the bond at low temperature loses its mechanical properties at the high temperatures.
2. The glass transition temperature, T_g, at which the polymer starts to lose its mechanical properties.
3. The amount of crosslinks within the polymer, which influences the rate of reduction in the properties of the polymer after T_g has been attained.

Introducing into the model the above data for FRP rods yielded an accurate calculated curve, which fits the behavior of the rods tested for pullout in this temperature range. It appears that the model can provide a useful tool to predict the bond strength of FRP rods at high temperatures, without the need to run a wide experimental program.

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