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The effect of heating and cooling on the bond strength between concrete and steel reinforcement bars with and without epoxy coating

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HIGHLIGHTS

- Concrete caps were used to simulate the test condition in an actual fire.
- The effect of epoxy coating on the bond under high temperatures was investigated.
- The effects of heating rate and cooling method on bond strength were studied.

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ABSTRACT

The purpose of this study is to investigate the temperature effects on the bond strength between concrete and steel reinforcement bars. For two different steel bars (epoxy-coated and uncoated bars), three experimental parameters (heating rate, target temperature, and cooling condition) are examined. At a target temperature of 200 °C, the epoxy-coated rebar has much higher bond strength than the uncoated rebar. However, in the specimens exposed to target temperatures higher than 200 °C, the test results show that the epoxy coated rebar has less bond strength than the uncoated rebar. Also, the test results demonstrated that as the heating rate and target temperature increase the bond strength decreases. The cooling method does not affect the ultimate bond stress of the specimens using uncoated rebar very much but can greatly affect specimens that contained epoxy coated rebar. A more in-depth study can be considered regarding the cooling effect on the bond strength.

1. Introduction

Fire has always been a real threat to the integrity of any structure. To improve the material property and structural safety under fire, the studies have been performed extensively through previous research over the past sixty years. Particularly, the terrorist attack to the World Trade Center on September 11, 2001 has stimulated a new sense of urgency on the theoretical and experimental studies associated with properties of construction materials and structural behaviors exposed to high temperatures. The behavior between concrete and steel reinforcement has been considered as one of the main characteristics in RC (Reinforced Concrete) structures.

Diederichs and Schneider [4] performed a pull-out test to investigate the variation of the bond strength on three different types of reinforcing steel (ribbed steel bars, plan round bars and deformed prestressing bars) under the heated and the cooled condition in the temperature range 20–800 °C. From the study, it was found that the bond strength is affected not only by the temperature level but also by the test procedure and the shape of bars. The results also showed the loss of bond strength for ribbed bars at constant elevated temperatures is of the same order of magnitude as the loss of high temperature compressive strength of concrete. At the same temperatures, plain round bars showed a sharper decrease in bond strength as compared with the other steel bars. Hertz [7] studied the anchorage capacity of reinforcing bars at normal and high temperatures. In the paper, a simple method for calculating the resistance to splitting was proposed, and a test method for determining the bond strength was presented. Morley and Royles [11] examined the effect of high temperatures upon the bond between the steel and concrete in reinforced concrete. The test parameters were different test conditions [stressed during heating (a steady-state bond stress of 3.70 N/mm^2 was applied) and loaded to failure when hot, stressed during heating and loaded to failure when cooled, no applied stress during heating and loaded to failure when hot, and no stress during heating and loaded to failure when

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cooled] and depths of cover. The specimens with smaller depths of cover were subjected to very small slip and bond specimens stressed during heating gave a slightly better performance than those that were not stressed. They [12] also examined the type of bar (plain and deformed bars of 16 mm diameter) and the effect of load cycling (for the deformed bar only) upon the bond after exposure to heat treatment using direct displacement measurements and monitoring acoustic emission. The results showed that deformed bars conducted a more effective bond performance than plain bars and load cycling decreased the maximum bond stress available. Also, for the temperature tested in excess of 250 °C, large irreversible slip took place during the cycling process. Lahnert et al. [8] suggested an experimental method to determine the local internal slip between steel and concrete directly at room temperature. Lowes et al. [10] presented a bond element for use in high-resolution finite element modeling of reinforced concrete structures subjected to general loading.

In previous research where bond strength at elevated temperatures has been evaluated and the test specimens did not model the heating effect accurately. Also, the effect of elevated temperatures on the epoxy coated rebar has not been extensively covered. This is important because the epoxy coated rebar behaves very differently from the uncoated rebar does in terms of bond [6]. With respect to cooling rate, little is known about its effects on bond strength for the uncoated rebar and even less is known about these effects on the epoxy coated rebar. In this study, the bond behaviors between concrete and steel reinforcements (two different bars: epoxy-coated and uncoated bars) are investigated with various experimental parameters such as heating rate, target temperature, and cooling condition.

2. Test variables and specimen preparation

2.1. Test variables

The test variables for this experiment include heating rates of 2 and 15 °C/min, target temperatures of 200, 400, 600, and 800 °C (holding time of 2 h at the target temperatures). For each rebar type and cooling rate, the specimen is left in the furnace until it returns to room temperature by natural means or water cooled with a constant flow (350 ml/s) at 15 °C.

This experimental study considers the cooling rate effect as a test parameter because, from reviewing published literature, the effect of different cooling regimes has not been studied thoroughly. Both the epoxy coated and uncoated rebar are subjected to these test conditions. However, the test condition subjected to water cooling after 2 °C/min heating rate is excluded for both epoxy coated and uncoated rebar due to test time limit. In the current experiment, the fast cooling rate of 15 °C/min was chosen to prevent potential spalling occurrence (a cooling rate of 30 °C/min. caused spalling damage of the concrete samples). Table 1 shows the test variables and terminology of the specimens.

Table 1
Test variables and terminology of the specimens.

Heating rate (°C/min) (Cooling method)	Target temperatures (°C)	Epoxy coated	Uncoated
2 (Natural cooling)	200	CR2_200N	UR2_200N
	400	CR2_400N	UR2_400N
	600	CR2_600N	UR2_600N
	800	CR2_800N	UR2_800N
15 (Natural cooling)	200	CR15_200N	UR15_200N
	400	CR15_400N	UR15_400N
	600	CR15_600N	UR15_600N
	800	CR15_800N	UR15_800N
15 (Water cooling)	200	CR15_200W	UR15_200W
	400	CR15_400W	UR15_400W
	600	CR15_600W	UR15_600W
	800	CR15_800W	UR15_800W

Note: C: coated; U: uncoated; R: heating rate; N: natural cooling: W: water cooling.

2.2. Specimen design and preparation

In this experimental study, Portland cement of Type I/II and crushed granite are used to make concrete specimens. The bulk specific gravity of the aggregates is 2.69. Admixtures of concrete are not used because the focus of this study is to investigate the bond effect between the steel bar and the granite concrete without the effect of admixtures. The mix was very dry due to the fact that the crushed granite sand contains very dry and fine particles. In this study, different w/c ratios were examined for workability and 0.71 was the lowest value with which the proper workability with slump value of 1.5 in. (38.10 mm) could be obtained [14]. The moisture content of the aggregates was measured using the test method B in ASTM D 2216. The absorption capacity of aggregates was 0.78%. By subtracting the water absorption capacity of the aggregates from the initial water content a final w/c ratio of 0.67 was obtained. The maximum size of coarse aggregate was 3/4 in. (19.05 mm). The RILEM pull-out test recommendation requires specific dimensions and strength of the concrete specimen, in which all of the dimensions depend on the diameter of the reinforcing steel (rebar). The diameter of the concrete specimen must be 10 times larger than the diameter of the rebar. In our test, #3 rebar (a diameter of 0.375 in.) is used which means the diameter of the specimen must be at least 4 in.

The bond length (a direct concrete and rebar interface) must be 5 times larger than the rebar diameter (2 in.). A bond length of this relation allows for the assumption that stresses across the bond interface are uniform; where in reality this stress is never uniform. Bond stress is nonlinear due to the wedge effect [1], shown in Fig. 1 occurring as a result of the pulling force. Therefore, as the bond length decreases, the effects of the nonlinear stress distribution over the bond length become less prevalent, and the distribution

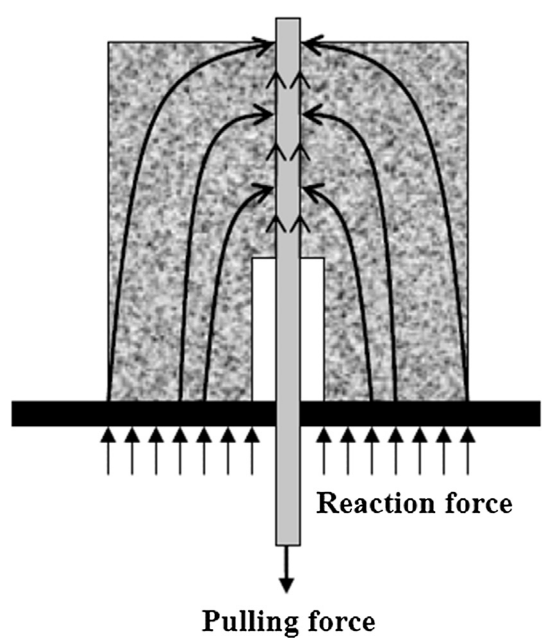

Fig. 1. Stresses distribution in the test specimen.