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The effects of material properties on bond strength between reinforcing bar and concrete exposed to high temperature

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HIGHLIGHTS

- RBS is residual bond strength.
- RBS between rebar and concrete exposed to high temperatures were investigated.
- A modified pull-out test setup was used in experimental studies.
- Math. equations were proposed to predict RBS of specimens exposed to high temperature.
- These equations can be used to assess the post-fire strength of concrete structures.

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ABSTRACT

The effects of material properties on bond strength between reinforcing bar and concrete exposed to high temperatures are investigated extensively using modified pullout tests. The specimen parameters include various bar diameters, rebar grades and concrete strengths. Three different concrete cubes with compressive strengths of 20, 34 and 44 MPa, 12, 16 and 20 mm rebar diameters and S220a, S420a and S500a rebar grades were utilized for the tests. In the experimental study, the tests were conducted on 150/300 cylinder specimens in which rebars are embedded vertically exposed to high temperatures (100, 200, 400, 600 and 800 °C) and cooled down. Furthermore, 150 mm cube and 100/100/300 mm prism specimens were used to determine compressive and flexural strength of concrete. Bond strengths of these specimens were compared with each other and then with unheated specimens at 20 °C. Experimental results indicated that residual bond strength between reinforcing bar and concrete decreases with increasing temperature. The first severe bond strength loss was observed for grade S220a at the range of 200–400 °C and for grade S420a and S500a at the range of 400–600 °C. The residual compressive strength is in tendency with the residual bond strength of S420a and S500a whereas the residual flexural strength corresponds agrees with the residual bond strength of S220a.

1. Introduction

The strength of a structure depends on the strength of the materials from which it is made. Having knowledge of the materials characteristics and behavior under load and environmental effects is fundamental to understanding the performance of reinforced concrete (RC) structures. Determining the mechanical properties of RC elements under environmental effects such as high temperature is as important as when they are under loads. Exposure to high temperatures during fire is one of the most damaging environmental effects for RC structures. Each of concrete and reinforcing bars has a different reaction to thermal exposures in itself and the behavior of the composite system after high temperature is difficult to model. As the concrete has the low thermal conductivity, it protects reinforcing bars to a certain depth of concrete cover from thermal exposures. Therefore, the complexities of temperature distributions between reinforcing bar and concrete exposed to high temperatures lessen [1]. When RC structural elements are exposed to high temperatures, a number of physical and chemical changes will occur mainly in concrete material.

The effects of high temperature on the mechanical response of concrete have been investigated since the middle of the twentieth century [2–5] and is still being studied today. The research found in the technical literature can be classified into two categories: materials testing and element testing. The results of materials

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testing provide information on the effects of temperature on the mechanical properties of concrete (such as compressive and tensile strength, modulus of elasticity, etc.), while the results from element testing is used to assess the fire resistance of reinforced-concrete structural elements (such as beam, columns, slabs). It was reported that the changes in the mechanical properties of concrete with temperatures could depend on several parameters such as the chemical and physical properties of the concrete constituents, the temperature to which the concrete structure had been exposed to, the size of the concrete structure as well as the external applied loadings and cooling conditions to which the structural member had been subjected to [1,6–16].

The previous studies on bond strength between reinforcing bars and concrete are less than the studies related to the mechanical properties of concrete exposed to high temperatures. The bonding behavior of reinforcing concrete at elevated temperatures has been investigated using pullout test specimens. Some of the related studies are the tests by Morely and Royles [17], Haddad and Shannis [18], Haddad et al. [19] and Bingol and Gul [20]. It was reported that there was a considerable loss in bond strength as the temperature was increased. The findings of these studies showed that the residual bond strength changed between 30% and 70% according to examined parameters such as the properties of concrete and rebar, the size of diameter and embedment length of rebar, the regime of heating and cooling etc. when subjected to temperatures in excess of 500 °C [17–20]. Furthermore, the effects of different parameters of concrete and reinforcing bars on behavior of bond strength at room temperature using pullout tests have been investigated [21–24].

In summary, the changes on the bond strength between reinforcing bars and concrete with temperatures depend on several parameters. For this reason, it is very difficult to quantify direct relationships between the temperature increase and decrease on the residual bond strength. In fact quantifying such relationships including the effects of different parameters with each other would be very useful for practicing engineers in order to assess the strength of existing buildings when exposed to fire.

In this experimental investigation, the results of 486 pull-out tests performed were presented with the aim of contributing to the experimental database and to a better understanding of the bond behavior between reinforcing bars and concrete exposed high temperatures. Bonding behavior was extensively examined for different types of concrete strengths, the rebar grades and rebar diameters to determine the effects of the investigated parameters. The concrete specimens were grouped in three series: Concrete-A, Concrete-B and Concrete-C with the cube compressive strength at 28-day of 20 MPa, 34 MPa and 44 MPa, respectively. Grades S420a and S500a deformed rebars and grade S220a plain rebar were chosen for the tests. The reinforcing bar diameters were 12, 16 and 20 mm. The changes over the bond strength between reinforcing bars and concrete of the 27 test series under elevated temperatures (20, 100, 200, 400, 600 and 800 °C) were analyzed by conducting the pullout tests, as well as the compressive and flexural strength tests.

2. Experimental studies

In this research, three concrete test series; (namely Concrete-A, Concrete-B and Concrete-C) were provided from ready-mixed concrete plant. Ready-mixed concrete was preferred in order to ensure homogeneity in each sample series throughout the experimental program. Ready-mixed concrete consists of the ordinary Portland cement (CEM I 42.5 R), crushed limestone aggregates (0–22 mm) and river sand (0–4 mm). The designations and proportions of the concrete mixtures for the three test series are given in Table 1. The cube compressive strengths at 28-day of test series were 20 MPa, 34 MPa and 44 MPa. Each test series consisted of thirty six $150 \times 150 \times 150$ mm cubes (6 trials, 6 cubes in each trial) and thirty six $100 \times 100 \times 300$ mm prismatic beams (6 trials, 6 beams in each trial). For comparing with heated specimens, three unheated specimens were tested to determine compressive and flexural strength of at 28-days and 90-days, respectively. The others were tested for failure to study the variation of the residual compressive and flexural strength with temperatures. The experiments were carried out using a closed-loop servo-hydraulic dynamic testing machine, with a capacity of 2000 kN. The samples were tested under strain control procedures. A constant axial strain rate was used throughout the experiments.

Three types and diameters of steel bars were used in preparing pullout specimens. The steel rebar types were grade S220a, S420a and S500a. The diameters of grade 220a plain round steel rebars and grade S420a and S500a deformed steel rebars were 12, 16 and 20 mm. The mechanical properties for all types and diameters of steel rebars are shown in Table 2.

The grades of S220a, S420a and S500a and the diameters of 12 mm, 16 mm and 20 mm reinforcing bars samples exposed to different temperature such as 200, 400, 600 and 800 °C temperature in the electrical furnace and then cooled slowly. Tension tests performed on the cooled samples by using universal test machine UTM). The residual yield and tension strengths obtained from the test results. These parameters compared with those of the room temperature (20 °C) samples [25].

The pull-out tests were performed to determine the bond strength. The pull-out test is easier than other test methods and more suitable for comparing relative bond properties [20,26]. A 150 mm diameter and 300 mm height cylinder mould was used to prepare the pull-out specimens for all temperature values. A single reinforcing bar 12, 16 and 20 mm in diameter was placed into the centre of concrete specimens with the embedment length of 250 mm. The produced specimens for pull-out tests were moist cured in the morning and evening for the first 7 days after casting, and then kept under existing laboratory conditions (20–22 °C) until 90th day (Fig. 1).

At the end of 90 days, the test cubes, beams and cylinder specimens, that were supposed to be tested at elevated temperatures, were first put into an oven and heated to a temperature of 100 °C for 48 h and then allowed to air dry. The electrical furnace used in this research as well as the heating regimes are shown in Fig. 2a and b. The samples were heated at a heating rate of 2 °C/min until the targeted test temperature was reached. The heating rate used in this study was chosen to be based on recommendations obtained from previous conducted researches [27,28]. However, it is worth mentioning that the rate of heating used is significantly lower than that of specified by ASTM E 119 [29], which is about 538 °C in the first 5 min. Once the targeted temperature was reached, it was maintained for 45 min to achieve the thermal steady state [30] and then allowed to cool down at a rate of 1 °C/min. The temperatures are chosen as 200, 400, 600 and 800 °C in this test programme. While the cylinder specimens with reinforcing bars embedment were being heated, the open-air end of bars were isolated with ceramic insulation coating. The specimens tested at 20 °C were considered as control specimens.

The pull-out tests were carried out. The pull-out test setup is shown in Fig. 3. The tests were performed using a servo-hydraulic universal test machine (UTM) with a capacity of 600 kN. A special attachment apparatus made with rigid steel plates used to pull the rebar rod from the specimen. The rod was fitted with grips on the machine and was pulled upward from the specimen until failure to obtain the ultimate load [31]. Total 486 specimens exposed different temperatures were tested. For each group, the average of 3 specimens' test results recorded.

3. Results and discussion

The results of present study are reported and discussed according to the following sequence. First, the compressive and flexural strengths of concrete exposed to high temperatures are discussed. Then, the bond strengths between reinforcing bar and concrete exposed to high temperature are evaluated using pull-out tests. Both the relationship between the grade of bar and bar diameter and the relationship between the grade of bar and concrete strength over bond strength are examined. Finally, a nonlinear empirical model that relates percentage residual bond strength to exposure temperature are developed.

Table 1
Concrete mix proportions (kg/m^3).

Series	Concrete-A	Concrete-B	Concrete-C
w/c	0.73	0.60	0.48
Cement	200	240	320
Fly ash	50	50	50
Water	182	172	175
Super-plasticizer	2.0	2.4	3.2
River sand 0–4 mm	366	–	–
Crushed sand stone 0–4 mm	627	951	878
Crushed stone II 6–12 mm	461	495	477
Crushed stone III 12–22 mm	445	443	462