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Mechanical properties and bond characteristics of different fiber reinforced polymer rebars at elevated temperatures

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HIGHLIGHTS

- FRP bars lost up to 55% of their tensile strength at a critical temperature of 325 °C.
- Concrete-FRP bond was significantly reduced upon exposure to high temperatures.
- FRP bars lost up to 81.5% of their bond strength at critical temperature of 325 °C.
- The analytical model, proposed in this study, showed good predictability.

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ABSTRACT

This paper presents the results of an experimental study on the effect of elevated temperatures on the mechanical properties of FRP bars and the bond behavior between FRP bars and concrete. Four types of reinforcement bars namely: basalt fiber reinforced polymer (BFRP), CARBON fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), and steel bars of 10 mm diameter were used. The results showed that the FRP bars suffered significant reductions in their mechanical properties upon exposure to high temperatures of up to 450 °C at which the GFRP and BFRP melted and lost their total tensile strength capacity. At a critical temperature of 325 °C, the FRP bars lost as high as (55% and 30%) of their tensile strength and elastic modulus, respectively. The percentage reduction in mechanical properties and bond strength was more pronounced in specimens with FRP bars than those with steel bars under elevated temperatures; the percentage reductions in bond strength between concrete and FRP bars reached as high as 81.5% after exposure to 325 °C. Based on the experimental results, an empirical model was proposed to predict the post-heating bond stress-slip relationship between the FRP bar and the surrounding concrete: a good agreement was noticed between the experimental results and the proposed model.

1. Introduction

During the last twenty years, many studies have been carried out on FRP materials. It was found that these non-corroding composite materials can be applied in concrete construction effectively as alternative to steel reinforcement in three different forms namely externally bonded FRP sheets or plates for repair or strengthening of reinforced concrete structure, main reinforcement in the form of FRP bars, and FRP prestressing tendons in prestressed concrete structures [1,2]. FRPs possess some advantages and disadvantages. Their advantages include high resistance to corrosion, high strength-to-weight ratios (10–15 times greater than steel), excellent fatigue characteristics (about 3 times that of steel), electromagnetic neutrality and ease as well as speed of application leading to reduce construction costs [1–3]. On the other hand, the disadvantages include high material cost, low ductility with low strain at brittle failure, low shear strength due to poor mechanical properties of the matrix, rapid and severe loss of bond, strength and stiffness at elevated temperatures, poor creep and expansion properties in the case of aramid FRP, and low resistance to alkali environments in the case of glass FRP [2–4].

Upon exposure to fire, FRP composites reach firstly the glass transition temperature T_g at which the resin changes from glassy state to leathery state followed by breaking of the chemical bonds, modular chains of the resin and bonds between the fibers at higher temperature known as the resin decomposition temperature T_d.

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Finally, the ignition and combustion of the composite occur at higher temperatures. The glass transition temperature (T_g) and decomposition temperature (T_d) of the polymer matrix were typically in the range of (65–120 °C) and (300–400 °C), respectively [1,4–8].

FRP bars to concrete bond mechanism depends on the bar's mechanical interlocking and the friction between the surface and the surrounding concrete. Chemical bond does not exist between the FRP bars and concrete contrary to the case with traditional bars. This is referred to the water repellent nature of the resin, used in the manufacture of FRP rebar [9]. Bar diameter, embedment length, FRP bar's modulus of elasticity, concrete strength, concrete cover and bars surface treatment are the main factors that were considered in the evaluation of the bond behavior [10–12]. In order to enhance bonds between FRP bars and concrete, different surface treatments are used such as sand coating, helical wrapping, molded deformation, irregular surface humps by adding excess of resin and braiding of the fibers [9]. Recent findings stated that the bond between FRP bars and concrete was inversely related to bar diameter due to the increase of voids formation at larger contact surfaces [13].

Bond strength between internal FRP reinforcements and concrete depends on the characteristics of resin polymer at the surface of the FRP bar [14,15]. The mechanical properties and microstructure of the resin polymer, especially at the surface layer of the rod, are negatively affected by high temperatures above T_g leading to a loss of bond between FRP and concrete [1].

Due to different transverse coefficient of thermal expansion of FRP bars and concrete, high radial pressure on the surface of the reinforcement is created causing bursting thermal stresses within the concrete. When these thermal stresses reach the concrete tensile strength (f_{ct}), micro-cracks occur leading to weakening of bonds especially when lower concrete covers are used [15–18]. The bond strength between FRP bars and concrete is severely affected even at relatively low elevated temperatures [2,19]. Rapid loss in bond strength, to 60% of room temperature strength, has been noticed at 100 °C. At 200 °C temperature, bond strengths decrease to 10–20% of its room temperature strength. Previous research confirmed that bond is totally lost at a high temperature of 300 °C and greater [1,20].

In this study, the effect of elevated temperature exposure on the mechanical properties of FRP/steel bars and the bond properties between these bars and concrete were investigated experimentally and empirically. Canadian standards, CAN/CSA-S806-02 [21] stipulated that FRP-RC structures fail when the FRP bar loses 50% of its strength at ambient temperature. Due to lack of data on the thermal mechanical properties of wide variety of FRP products, available in the market, the critical temperature for FRP that affects their properties and bond strength with concrete was not precisely defined [22]. Based upon various literature works, the critical temperature can be assumed to range from 250 °C to 500 °C [7,23–27]. The current study showed that the FRP bars had lost as high as (55%, 30% and 81.5%) of their tensile strength, elastic modulus and bond strength with concrete after exposure to 325 °C, respectively.

2. Experimental program

2.1. Materials

2.1.1. Reinforcement bars

Four types of 10 mm diameter reinforcement bars are considered in this work including helically wrapped glass fiber reinforced polymer (GFRP), sand-coated carbon fiber reinforced polymer (CFRP), helically wrapped basalt fiber reinforced polymer (BFRP) and deformed steel bars (Fig. 1). The properties of the FRP bars used as provided by the manufacturer are presented in Table 1, whereas the properties of the steel bars before and after exposure to 450 °C are presented in Table 2.

2.1.2. Concrete

Normal strength concrete having 28-days-compressive strength of 40 MPa and average measured slump of 90 ± 2 mm was used in preparing the various specimens. Ordinary Portland cement Type-I, crushed granite coarse aggregate of 10 mm maximum size and natural river sand of 2.7 specific gravity and 0.6% moisture content were used. The concrete mixture proportions are presented in Table 3.

2.1.3. High tensile strength epoxy

Epoxy adhesive having the commercial designation CONCRESIVE 1441S, and manufactured by BASF-Malaysia, was used to adhere grip steel pipes to the FRP bars free ends before tension and pullout tests. These steel pipes provide a confinement pressure on the bar to prevent its slippage or local failure due to the damage of the bars ends under tension. After 7 days of curing, this epoxy has tensile, compressive and shear strengths of 10, 83 and 35 MPa, respectively, whereas its density and elastic modulus are 1.25 kg/L and 4600 MPa, respectively.

2.1.4. High temperature thermal insulation coating

High-temperature thermal insulation coating (RLHY-12) of 0.03 W/m.K heat conductivity, manufactured by Beijing Ronglihengye Technology Corporation, Ltd – China, was used to insulate the free part of the FRP bars pullout specimens and protect them from direct fire flames during heating.

2.2. Specimens preparation

2.2.1. Preparation of tensile testing specimens

BFRP, CFRP, GFRP and steel bar specimens of 600 mm length and 10 mm diameter were prepared for tensile tests. A total of 18 specimens of each bar type were used. Three of them were tested at ambient temperature and used as controls while the remaining fifteen specimens (in triplicates) were exposed to different elevated temperatures of 125 °C, 250 °C, 325 °C, 375 °C and 450 °C. The specimens were heated up with 10 °C/min heating rate in an electric furnace allowing the hot air to circulate in the furnace until reaching the required target temperature, and then kept at

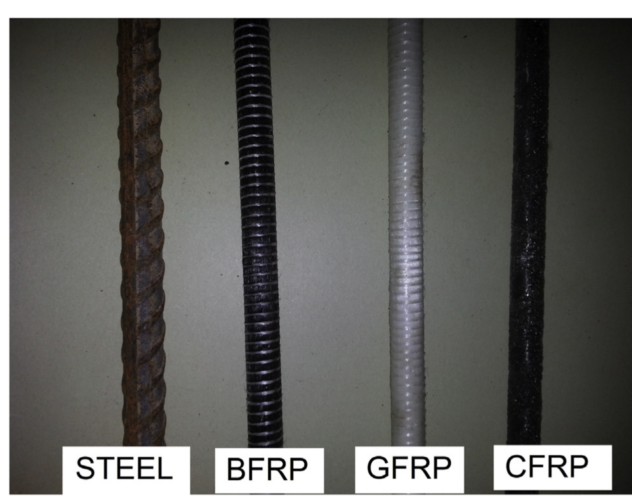

Fig. 1. Different reinforcement bars used.