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Material characteristics and residual bond properties of organic and inorganic resins for CFRP composites in thermal exposure

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HIGHLIGHTS

- Characteristics of various resins for CFRP application at high temperature are studied.
- Curing time and exposure temperature are important parameters.
- Inorganic resin shows thermal stability, while organic resin provides strength.

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ABSTRACT

This paper presents the residual characteristics of organic and inorganic resins for structural retrofit using carbon fiber reinforced polymer (CFRP) composites exposed to thermal stress states. A three-phase experimental program is carried out to study the behavior of the inorganic resin, CFRP composites, and resin-concrete interface at elevated temperatures ranging from 25 °C to 200 °C. The properties of the inorganic resin demonstrate strong dependency on curing time and are influenced by the degree of temperature exposure. CFRP composites show a decrease in strength and modulus with an increasing temperature due to the degradation of bond between the fibers and resin. The inorganic resin exhibits better thermal stability than the organic resin, whereas the former illustrates a lower strength than the latter because of insufficient stress-transfer. The composites have failed abruptly, regardless of resin types. The interfacial fracture energy of the resins is reduced with temperature, including the deteriorated morphology of the interface between the concrete substrate and the resin.

1. Introduction

Retrofitting existing concrete structures is often necessary to upgrade their structural capacity because of their performance degradation over time. Among many possible rehabilitation options, the one using carbon fiber reinforced polymer (CFRP) composites has demonstrated promising consequences [1]. CFRP sheets may be attached to the substrate of a deteriorated concrete member with a bonding agent. CFRP-retrofitted members exhibit improved load-carrying capacity and serviceability [2]. The bonding agent in such an application plays an important role since it binds carbon fibers to transfer stresses and maintains structural integrity between the retrofitted member and CFRP. Organic resins (e.g., polyepoxide having an organochlorine compound such as epichlorohydrin) are broadly used in the rehabilitation community. These adhesives include several favorable characteristics, namely, high strength, resistance to impact and vibration, wide applicable ranges, and rapid curing; on the other hand, they also include a critical drawback: susceptibility to high temperature exposure. The performance of an organic resin is significantly degraded when subjected to a temperature higher than its glass transition temperature. The reason is that the molecular chains of such a polymeric material relax with temperature and its crystalline structure experiences a phase transition into a liquid-like state accordingly [3]. To overcome this technical issue, alternative bonding agents may be required.

Inorganic resins have occasionally been used for CFRP application because of the following advantages: low material costs, resistance to thermal stress and UV radiation, environmental durability, and workability [4–7]. Badanoiu and Holmgren [8] performed a pull-out test to examine the failure mode of inorganic-resin-based CFRP. Focus of the experimental work was the variable amount of polymeric compounds mixed in the resin. Load-carrying capacity of test specimens increased with increasing polymer contents due to the improved interfacial bond between

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the fibers and resin. Scanning electron microscopy images showed the interfacial behavior of the specimens. These observations indicate that regional bond between the resin and fibers was a crucial parameter for CFRP-retrofit. Toutanji et al. [5] reported the fatigue behavior of reinforced concrete beams strengthened with a CFRP-inorganic resin system. Fatigue life of strengthened beams increased owing to the contribution of the CFRP system. Taljsten and Blanksvard [9] provided a concise review of organic and inorganic resins for CFRP application and conducted an experimental project: reinforced concrete slabs and beams were retrofitted using CFRP grids bonded with an organic or inorganic resin. Flexural capacity of the members having a combination of the CFRP and inorganic resin was comparable to that with the organic resin counterpart. Toutanji and Deng [10] compared the behavior of reinforced concrete beams retrofitted with CFRP composites bound by an organic or inorganic resin. Emphasis of the test was given to strength, ductility, cracking pattern, and failure mode. Load transfer mechanisms between these two resins were distinct and the inorganic system appeared to be more brittle when failure occurred. Hashemi and Al-Mahadi [7] examined the behavior of reinforced concrete beams strengthened with CFRP textiles embedded in an inorganic resin. Test results encompassed load-carrying capacity, strain development along the CFRP, and failure modes. A finite element model was constructed to predict test data. The beams with CFRP textiles bonded with the inorganic resin showed lower failure loads than those with conventional CFRP impregnated in an organic resin. The inorganic resin achieved noticeable composite action with the concrete substrate.

According to the literature search given above, concrete members retrofitted with CFRP show enhanced behavior whether bonded with organic or inorganic resins from a structure-level perspective. Limited information is, however, available on the material-level performance of CFRP composites with these resins for retrofitting existing concrete structures, in particular the inorganic constituent. Of interest are their behavior subjected to elevated temperatures and corresponding bond capacity. It is worthwhile to note that, despite recent endeavors on inorganic resins for CFRP application, most existing research has been dedicated to the behavior of CFRP-retrofitted members at room temperature. This paper deals with an experimental study concerning (i) the material characteristics of carbon fibers embedded in an organic or inorganic resin, forming CFRP composites, when exposed to elevated temperatures and (ii) the interfacial response of these resins bonded to a concrete substrate. Emphasis of research was placed on the residual properties of these retrofit materials after exposing to high temperatures, rather than their properties during thermal exposure, because the functionality of retrofitted members after experiencing a fire event is dependent upon the residual properties of the CFRP system.

2. Experimental program

A three-phase test program was designed to examine (i) the material response of an inorganic resin (Phase I), (ii) the performance of CFRP composites with an organic or inorganic resin (Phase II), and (iii) the behavior of resin-concrete interface (Phase III), when exposed to elevated temperatures. Fundamental properties of the organic resin were not examined because relevant studies provided sufficient test results [11,12]. Below is a summary of the experimental program.

2.1. Materials

The organic resin used was a two-part epoxy adhesive. This low viscosity material (1600 cps at 20 °C) consists of parts A and B that are blended at a weight ratio of 76% and 24%, respectively, and stirred until a homogeneous mixture is obtained. Upon curing of the mixture for 7 days at room temperature, a tensile strength of 50 MPa with corresponding modulus of 3 GPa is provided [13]. The nominal glass transition temperature of the epoxy is 71 °C. An inorganic resin was manually mixed in the laboratory at a water–matrix ratio of 0.38. As per the manufacturer's recommendation [14], the resin powder was first blended with approximately 90% of the required water for 3 min and the remaining water was poured for an additional mix of 3 more minutes. The mixed resin can uniformly be applied to a substrate using a spatula with a thickness of 2 mm. The specified compressive strength and secant elastic modulus of the inorganic resin are 29 MPa and 6 GPa at 28 days, respectively. Unidirectional carbon fiber fabric has a specified tensile strength of 3800 MPa with a modulus of 227 GPa, based on its nominal thickness of 0.165 mm [15]. The fabric was embedded in the organic or inorganic resin to form a CFRP composite. For interfacial testing (to be discussed), concrete was mixed in the laboratory with a specified compressive strength of 40 MPa with the following constituents: cement (500 kg/m^3), water (190 kg/m^3), sand (760 kg/m^3), and coarse aggregate (1050 kg/m^3).

2.2. Test specimens

Experimental specimens were prepared to meet the objectives of the three test phases. Cubes (50 mm × 50 mm × 50 mm) were cast to examine the temperature-dependent compressive strength of the inorganic resin, as shown in Fig. 1(a), as per ASTM C109-12: *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars*. A Teflon mold was used to produce dog-bone coupons based on ASTM D638-10: *Standard Test Method for Tensile Properties of Plastics* (Fig. 1(b)). Coupons (15 mm wide × 200 mm long) were also made to measure the tensile properties of the CFRP associated with the organic and inorganic constituents (Fig. 1(c) and (d), respectively), including the equivalent fiber thickness of 0.165 mm, based on ASTM D3039 *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*. It should be noted that the CFRP coupons were shaped by grinding the unnecessary residue resin along their edges: Fig. 1(d) compares shaped and unshaped coupons. To study the interfacial behavior of the organic and inorganic resins applied to a concrete substrate, three concrete blocks (50 mm wide × 50 mm deep × 120 mm long, each) were bonded with these resins, as shown in Fig. 2. Prior to bonding, the surface of the concrete blocks was grit-blasted and an air compressor was used for cleaning. All test specimens were cured at room temperature according to the manufacturers' guidelines (e.g., CFRP with the inorganic resin was cured for at least one week, while that with the organic resin was cured for one month).

2.3. Thermal exposure

The prepared specimens were exposed to elevated temperatures for 3 h, from 25 °C to 200 °C with an interval of 25 °C (each test category was subjected to the respective predefined temperature for 3 h). It is worthwhile to mention that typical fire exposure time of CFRP-retrofitted structural members is 3 h and adequate insulation layers keep temperature below 200 °C within this timeframe [16]. Electric furnaces were employed to accomplish the predefined heat exposure, as shown in Fig. 3. Prior to heating the specimens, the performance of the furnaces was calibrated using thermocouples (Fig. 3(c)). After 3 h of thermal exposure, the specimens were cooled down to room temperature for residual testing. Identification codes for each test category were given as follows. Table 1 indicates the compression (CC) and tension (CT) of the inorganic resin cubes and coupons, respectively, with an exposure temperature for a residual test and repetition. For example, CT25-3 points out that the tension coupon was subjected to 25 °C and was the third repetition at this temperature. Table 2 shows the CFRP tensile coupons with the organic (FO) and inorganic (FI) resins exposed to certain temperatures. Table 3 summarizes the interface specimens bonded with the organic (IO) and inorganic (II) resins. The format of notations used in Tables 2 and 3 (i.e., temperature and repetition) was identical to that of Table 1.

2.4. Test setup and instrumentation

The resin cubes were monotonically loaded in compression until material crushing occurred, as shown in Fig. 4(a). Also tested was the time-dependent strength variation of the inorganic resin because the properties of such a material change with curing time. The CFRP coupons were tensioned (Fig. 4(b)) and the interface specimens were loaded as well (Fig. 4(c)). Strain gages were bonded to selected specimens to measure tensile strain (e.g., Fig. 1(c)) and no gages were used for compressive testing. All test data were recorded in a data acquisition system, including load, strain, and displacement.

3. Test results and discussion

3.1. Phase I: characteristics of inorganic resin

3.1.1. Effect of curing time

Fig. 5 exhibits the strength variation of the inorganic resin with respect to curing time. Some experimental scatter was imperative in all specimens due to their manual-mixing nature; for example the coefficients of variation of these compressive specimens ranged between 0.09 and 0.39. Typical failure modes in