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A study of the practicality and performance of CFRP applications using post-curing at moderately elevated temperatures

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ABSTRACT

The application of post-curing influences the final structure of the adhesive by extending the curing reaction of the epoxy to help it reach its full physical characteristics, such as ultimate cross-link density and T_g. This study explores the practical means of post-curing CFRP/concrete systems at moderately elevated temperatures, namely at 60 °C, using bonding adhesive under specific operating conditions. Adhesive samples and CFRP/concrete specimens were subjected to a post-curing regime at 60 °C after different periods of ambient temperature curing (3 h, 6 h and 72 h). The outcomes from this work will provide guidelines for post-curing applications for outdoor structures in an attempt to find practical methods to improve the bonding capacity of CFRP/concrete systems under more extreme environmental conditions.

1. Introduction

The advantages of fibre-reinforced polymer (FRP) composites have strongly encouraged the application of such advanced composites for civil infrastructures as an alternative to traditional techniques for strengthening and retrofitting. The most commonly used FRPs for strengthening and retrofitting purposes are carbon fibre-based (CFRP). The key advantages of CFRP are its low density, high strength-to-weight ratio, chemical and corrosion resistance, low coefficient of thermal expansion [1] and good fatigue resistance [2]. In addition, CFRP can be used for different strengthening applications such as shear [3,4], flexural [5] and torsion [6]. The function of the adhesive in the strengthening system is to transfer stresses between the CFRP materials and the concrete members. In the case of the wet-layup method for CFRP applications, the adhesive resins work as matrices for the composites, as well as bonding the CFRP materials to the adherent. The adhesive interlayer is therefore an important part of the CFRP, since it forms a resin continuum between the CFRP and the concrete [7]. However, when the operational temperature is close to or exceeds the glass transition temperature (T_g) of the adhesive, the CFRP starts to lose its ability to transfer stresses from the concrete to the strengthening fibres. This is due to the fact that epoxy resins are very sensitive to heat and soften [8], causing a rapid decrease in efficacy of the entire strengthened system.

The curing process of some room temperature cured adhesive systems (thermosetting polymers) requires additional heat input to lift the samples temperature above the glass transition temperature (T_g) which results from the ambient cured system. Such an ambient cure cycle eventually leads to cessation of the reaction because the system becomes glassy and the moieties become entrapped and unable to move and thus react. By heating the samples above this value of T_g, the reactive groups again become mobile and cure can proceed and high levels of crosslinking achieved. The extent of the curing reaction influences the final network structure of the adhesive, which changes the bulk properties of the cured epoxy network [9]. We have previously shown [10] that post-curing at moderately elevated temperatures (60 °C) for 4 h is an effective method to improve adhesive properties (increasing T_g, modulus and tensile properties). The interfacial bond in the CFRP/concrete system is also found to improve by post-curing at 60 °C, with little negative influence on the adherent properties (the concrete substrate), compared with post-curing at high temperatures (2 h at 100 °C followed by 2 h at 140 °C) [11]. It is thus desirable to investigate more detail the post-curing process at moderately elevated temperatures to understand clearly the effect of post-curing after ambient temperature curing periods of less than 7 days. This will help to develop methods and curing regimes which are applicable to post-curing outdoor structures.

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2. Materials

The adhesive is a commonly-used thermosetting polymer for bonding CFRP materials to concrete substrates. It is a commercially-available bonding adhesive, MBrace® Saturant (BASF, Chemical Construction, Pty. Ltd, Australia) used to externally bond CFRP material to concrete substrates. The adhesive is a two-part system of ambient temperature curing with a mixing ratio of (100:30) (Part A:Part B) with a glass transition temperature (T_g) of 70 °C (DMTA) for ambient temperature curing [10]. The T_g is 83 °C (DMTA) with the application of post-curing at moderately-elevated temperature (60 °C) for 4 h after more than 7 days of ambient temperature curing [11].

The CFRP material used in this work is a normal modulus CF fabric commercially available as MBrace CF 130 (S & P C-Sheets 240) supplied by BASF Chemical Construction Pty. Ltd, Australia. CF-fabrics are of 240 GPa fibre modulus and 3800 MPa of tensile strength according to figures provided by the manufacturer.

Concrete specimens of 75 × 75 × 250 mm dimensions were produced from normal strength concrete mix. The average recorded compressive strength of the concrete was 35 MPa after 28 days of curing.

3. Fabrication of CFRP/concrete samples

The surface of the concrete was prepared for bonding by sandblasting to remove dirt and latent material to expose the coarse aggregates from the area for strengthening with CFRP. The bonded area was 150 × 70 mm. The concrete surface was then cleaned using a brush to remove any dust. A primer, which is a two-part epoxy adhesive that cures at ambient temperature, was placed on the cleaned area of the concrete by applying a thin layer and specimens were left for 1 h at ambient temperature for curing.

A wet lay-up method was used for CFRP application. In this method, CF fabric was saturated with the adhesive and placed on the bonded area using a roller. CFRP/concrete samples were then left at ambient conditions for more than 7 days. In the case of tests involving elevated temperature exposure, Type-k thermocouples were used to obtain the temperature within the adhesive layer. One thermocouple was placed in a central position on the concrete surface before the application of the epoxy layer, as shown in Fig. 1.

4. Test procedure

4.1. Adhesive heat of reaction

The heat reaction of MBrace® Saturant epoxy adhesive was monitored using thermocouples, in order to identify the temperature of the adhesive prior to post-curing and its effect on the final properties of the adhesive. Immediately after mixing the monomer (Part A) with the curing agent (Part B), two thermocouples were placed within the mixture and logged by computer as a function of time.

4.2. Adhesive glass transition temperature (T_g)

4.2.1. Dynamic Mechanical Thermal Analysis (DMTA)

DMTA was used in this work to obtain the glass transition temperature and modulus for post-curing samples after different periods of ambient temperature curing (3 h, 6 h and 72 h). Solid adhesive samples were placed in a medium DMTA fixture of a dual cantilever mode. The dimensions of these samples were 40 × 5 × 2 mm for length, width and thickness respectively. The strain amplitude was set at 0.05% with 1 Hz frequency. The temperature was scanned from 25 °C to 150 °C with a heating ramping rate of 2 °C/min.

4.2.2. Differential Scanning Calorimetry (DSC)

DSC was used to thermally scan solid samples of ambient temperature curing and for post-cured samples from 20 °C to 120 °C at 10 °C/min heat scanning rate. The samples were then held isothermally for 1 min at 120 °C and then cooled from 200 °C to 20 °C at the same scanning rate and held for 1 min at 20 °C. The final heating cycle was then undertaken at 10 °C/min, as for the first cycle.

4.3. Bond strength tests for CFRP/concrete system

4.3.1. Ambient conditions

In total, 10 CFRP/concrete samples were tested in ambient conditions. Eight of these samples were post-cured after different periods of ambient condition curing (3 h, 6 h, 72 h and more than 7 days). Two CFRP/concrete samples with ambient temperature curing only (control samples) were also tested under the same conditions. Single-lap shear CFRP/concrete samples were placed in a test set-up, which was fixed into the Instron loading machine and all samples were tested under uniformly-increasing loading, with a displacement rate of 0.5 mm/min until failure.

The strain measurements along the bond length (150 mm) of single-lap shear samples were conducted using strain gauges. Five strain gauges (Micro-Measurements & SP-4) were positioned longitudinally on the CFRP. Four were placed within the bonded area and one gauge was positioned closer to the loaded edge (outside the bonded area). The distance between the gauges was 35 mm from centre to centre. The first gauge was positioned within the first 20 mm of the un-bonded CF fabric at a distance of 7 mm from the loaded edge. The other four gauges were located within the bonded area.

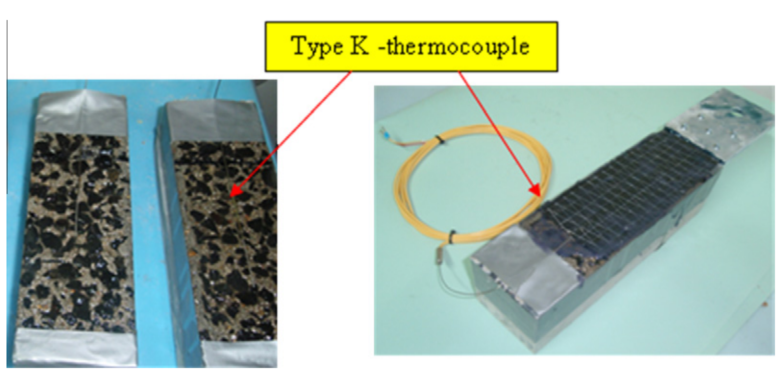

Fig. 1. Sample preparation for elevated temperature testing.