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Bond behaviour between NSM CFRP strips and concrete at high temperature using innovative high-strength self-compacting cementitious adhesive (IHSSC-CA) made with graphene oxide

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HIGHLIGHTS

- Significant resistance to high temperature of IHSSC-CA was indicated in this study.
- NSM CFRP strengthened samples with IHSSC-CA at 21 °C showed high bond strength.
- Placing the cover layer of IHSSC-CA was found efficient to protect bond area.
- Proposed fitting equations are able to simulate the experimental aspects reasonably.

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ABSTRACT

Strengthening of reinforced concrete (RC) structures using the near-surface mounted (NSM) fibre reinforced polymer (FRP) method is becoming an attractive technique for upgrading the existing structural elements. The exposure of the NSM FRP strengthening system to high temperatures greatly affects the bond between FRP, adhesive material and the concrete substrate. Organic adhesives are widely used in the NSM strengthening technique. However, their low fire resistance is a major drawback. This study investigates the performance of NSM carbon FRP strengthening technique using single-lap shear tests (pull-out tests) with innovative high-strength self-compacting cementitious adhesive (IHSSC-CA) under high temperatures. Graphene oxide and cementitious materials were used to synthesise the IHSSC-CA. Single-lab shear tests were conducted on NSM strengthened specimens which were exposed to high temperatures of 800 °C. The results obtained from the pull-out tests signifies that the samples made with IHSSC-CA were less affected by high temperature, and maintain considerable residual bond strength. Theoretical equations are proposed to simulate the effect of high temperature on bond strength.

1. Introduction

The Near-Surface Mounted (NSM) fibre reinforced polymer (FRP) strengthening and repair technique has been widely used to restore or increase the strength of reinforced concrete (RC) structures. In this method, FRP rods or strips are bonded into slits cut into the external surface of the concrete with the appropriate adhesive (typically an epoxy). The NSM FRP strengthening technique has become adopted practice in the construction industry for FRP strengthening applications because of the sensitivity of the Externally-Bonded (EB) FRP strengthening technique resulting in premature de-bonding ([18,29]. Despite the fact that the NSM FRP strengthening technique using organic adhesives shows a suitable bond between FRP-organic adhesive and concrete under ambient conditions, the bond under fire remains a serious problem due to the sensitivity of organic adhesives to high temperatures [19,29,12]. It has been reported that the glass transition temperature (Tg) of epoxy adhesive has a negative impact on the bond strength of NSM FRP strengthening systems. At 50 °C failure occurs by splitting of the resin and at 100 °C by pull-out of the FRP [27]. In addition, the fire behaviour of organic adhesives is associated with smoke, toxicity and flame spread [31,22]. This material is therefore considered inadequate for fire conditions when the temperature can increase up to 1000 °C. Within the last few years, many studies investigated the possibility of enhancing the performance of organic adhesives to make them suitable under high temperature, but no significant progress has been achieved [24]. Therefore, an

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alternative adhesive material such as cementitious grout is being sought to overcome this problem. Generally, cementitious materials undergo physical and chemical changes when exposed to high temperatures. As a result, degradation of mechanical properties occurs gradually, compromising resistance to heat transfer and causing further fire penetration. However, this happens in a wide range of temperatures (400 °C–1200 °C) and for a considerable time [26]. In recent years, a number of studies have been published on the use of different types of cementitious adhesives for FRP strengthening [12,17,15,28]. However, the mechanical strength of these cementitious adhesives is not sufficient. The maximum 28-day compressive strength of 84 MPa was reported for the material used by Petri [28], and for 28-day tensile strength, it was 5.1 MPa, as recorded by Erdem [17]. In order to find an alternate solution, IHSSC-CA was developed, which has 28-day compressive and tensile strengths of 101 MPa and 13.8 MPa, respectively [25]. This high mechanical strength is a key factor in the development of high bond strength in CFRP strengthening systems. Graphene oxide (GO), one of the most commonly used derivatives of grapheme, was used to synthesise IHSSC-CA. In relation to the enhanced thermal properties of the host material, studies have reported the successful utilization of GO [23,33]. Recently, Wicklein et al. [30] reported the production of super-insulating and fire retardant foams that perform better than the traditional polymer-based insulating material. In this study, the performance of IHSSC-CA in high temperature was investigated.

The effectiveness of the NSM CFRP strengthening technique depends on the bond between the concrete substrate and the CFRP laminates. Direct pull-out test, using single- or double-face shear test, and beam pull-out test were carried out to determine the interfacial bond between FRP and concrete. Although the beam pull-out test can capture the actual bond behaviour better than the direct pull-out test, it is less manageable due to the requirement of larger test specimens. Therefore, direct pull-out test is preferred ahead of beam pull-out test.

As the bond between FRP-adhesive material and concrete is vital for a successful strengthening system, it is necessary to understand bond behaviour under high temperatures using single-lap shear tests. This is considered as a preliminary study in order to adopt IHSSC-CA in full-scale members with NSM CFRP strengthening technique.

2. Experimental work

2.1. Synthesis of IHSSC-CA

An automatic mortar mixer in compliance with EN 196-1 [9], EN 196-3 [10] and EN 480-1 [11] specifications was used to mix the cement-based adhesive. The materials include general purpose ordinary Portland cement compatible with the Australian standard [3]; some cementitious materials and super-plasticizer. The dry materials were mixed for 2 min at high speed. Then GO was added, followed by the amount of water and super-plasticizer. Super-plasticizer has been used to maintain flow ability of IHSSC-CA, which is an important factor for placing cement-based adhesive in grooves. Further details are provided in Mohammed et al. [25]. Table 1 shows the physical properties of the IHSSC-CA as tested under laboratory conditions.

2.2. Mechanical strength of IHSSC-CA

Compressive strength testing was carried out as per the ASTM C39-16b [4]. The test was conducted for 5*5*5 cm cubic specimens. Tensile strength of cylindrical specimens of size 5 cm dia. and 10 cm high was carried out using the ASTM C496-11 [5]. The tests were conducted at ambient temperature and at various high temperatures.

3. Single-lap shear tests (pull-out tests)

3.1. Specimen details

A total of 18 concrete prisms 75 × 75 × 250 mm were prepared and tested. A normal-strength concrete was used to cast the prisms. The mix design proportions by weight, according to the [1], is shown in Table 2 with slump and mechanical strength of concrete. The maximum size of gravel was 14 mm and the water/cement ratio was 0.6. Slump was tested according to the ASTM C143-15a [6], which was found to be 50 mm (medium workable mix). MBrace CFRP laminate 210/3300 with unidirectional carbon fibre in an epoxy matrix was used in this study. The CFRP laminate was tested according to the ASTM D3039-14 [8] to determine the tensile strength, modulus of elasticity, and ultimate strain. The CFRP laminate properties as provided by the manufacturer and as laboratory tested are included in Table 3. The bonding length was designed to be 180 mm and was kept constant for all series. Details of the NSM CFRP specimens are shown in Fig. 1.

3.2. Application of IHSSC-CA and CFRP strips inside groove

Fig. 2 shows the steps in the application of IHSSC-CA inside the groove. After 28 days of moist curing at laboratory temperature (21 °C), the concrete prisms were ready for strengthening using NSM technique. A table-mounted saw was used to cut a groove 5 × 30 mm suitable for placing a CFRP strip of size 1.4 × 20 mm as shown in Fig. 2(a). According to ACI 440.2R-08 [2], the minimum grooves' dimension should be at least 3 times FRP strip's thickness and 1.5 times FRP strip's width. The groove was cleaned using compressed water to remove dust and broken concrete. The CFRP laminate was cut to the required size and 50 mm was left unbonded at the loaded end to avoid specimen edge failure. A 100 mm length was extended outside the specimen to be attached to aluminium plates (50 × 50 × 2 mm) to enable load application. Before applying cement-based adhesive, the groove was wetted with water. Then, the groove was filled with IHSSC-CA using an injection gun (see Fig. 2(b)). Next, the CFRP strip was inserted into the groove to the required depth, as shown in Fig. 2(c). Finally, any excess cement-based adhesive was removed and the surface of the concrete prism was levelled, as shown in Fig. 2(d). Owing to high fluidity and self-consolidation of IHSSC-CA, ease of application was highly satisfactory. In addition, the self-consolidation property of IHSSC-CA prevents the formation of air voids inside the groove which may affect the bond between the CFRP strip and the concrete surface. To avoid exposure of the CFRP to high temperature, the top surface of the bond area was covered with a layer of IHSSC-CA. The thickness of this layer was chosen to be equivalent to the exposure temperature. The thickness of the cover layer for 400 °C and 600 °C was 20 mm and for 700 °C and 800 °C it was

Table 1
Physical properties of IHSSC-CA.

Flow from ASTM C1437 [7]	Initial setting time (min)	Final setting time (min)	28-day tensile strength (MPa)	28-day compressive strength (MPa)
7.5%	120	420	14.3	113