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Bond performance of NSM CFRP strips embedded in concrete using direct pull-out testing with cementitious adhesive made with graphene oxide

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HIGHLIGHTS

- IHSSC-CA is easier to use for NSM CFRP application than epoxy and polymer cement adhesives.
- IHSSC-CA shows better composite action with concrete and CFRP than polymer cement and epoxy adhesives.
- The results confirm the effectiveness of using IHSSC-CA to improve the NSM CFRP technique.
- An analytical model is proposed to predict the ultimate pull-out force (bond strength).

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ABSTRACT

Concrete structures are normally strengthened using fibre reinforced polymer (FRP) with epoxy adhesives and polymer cementitious mortars. Epoxy adhesives have significant issues, such as the release of toxic fumes throughout curing, loss of strength and stiffness when exposed to hot temperatures, and low permeability and weakness to UV radiation. In the case of polymer cementitious adhesives, their properties are adversely affected by hydrothermal conditions. An innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA) has recently been developed by the authors which uses graphene oxide and cementitious materials. This paper presents the bond response of carbon FRP strips bonded to concrete substrate using near-surface mounted (NSM) technique with IHSSC-CA, epoxy and polymer cement-based adhesives using direct pull-out tests. The behaviour of each adhesive is presented and compared and the local bond-slip relationship is calculated. Finally, an analytical model is proposed to predict the ultimate pull-out force (bond strength). The results of this study confirm the effectiveness of using IHSSC-CA to improve the bond strength, stiffness, CFRP strip utilisation, ductility and residual strength of NSM CFRP system. Moreover, the proposed analytical model can simulate experimental conditions reasonably well.

1. Introduction

Fibre reinforced polymer (FRP) has been widely used to strengthen or repair the deficient reinforced concrete (RC) structures using near-surface mounted (NSM) system. In this technique, FRP composite is bonded into grooves, cut into the concrete surface, using a suitable adhesive. The NSM-FRP system has been widely adopted in the civil construction applications due to early de-bonding of the externally-bonded (EB) FRP technique [1,2]. Also, the NSM FRP technique be able to keep the FRP composite safe from harsh environmental effects [3]. Moreover, it removes the need for surface preparation, and has the advantage of reduced the installation time [3–5]. The idea of NSM-FRP system initiates in the 1940s as of the rehabilitation of concrete building in Europe [6].

The most used tests to study the bond response between FRP, adhesive and concrete are the beam, double and single lap tests. However, beam pull-out testing has many disadvantages, including the large size of the specimens, and the difficulty of monitoring crack initiation and development during the test. Direct double-face shear test overcomes the drawbacks of the beam pull-out test. However, any deviations in the positions of the FRP bar or strip can have flexural effects, which may lead to errors in the test results.

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Direct single-face shear test is an attempt to overcome this issue, especially by using fully restraining support at the top of the concrete prism, at the loaded end, to prevent eccentric loading during the test.

A limited number of research study have been published related to the bond between FRP-epoxy adhesive and the concrete substrate under monotonic loading using NSM pull-out tests [7–14]. The effectiveness of the NSM method increases as the width of CFRP strips increases, and CFRP strips with large aspect ratios (width/thickness) are more efficient [7]. The pull-out force increases as the bonded length increases [8]. The ultimate pull-out capacity and NSM CFRP utilization increase with the increase of the bonded length, while the bond-strength decreases. Moreover, the strength of the concrete has a minor effect on the pull-out capacities [9]. The ultimate pull-out force and CFRP strip utilization increase as the bonded length increases, and the strength of the concrete has a negligible effect on the pull-out capacity [10]. The local bond stress-slip relationships are determined based on the readings of strain gauges attached to CFRP strips within the bonded length [11]. Increasing the embedded length of the CFRP bars, for the same groove size, leads to increases in the pull-out capacity. In addition, increasing the groove size, for the same bonded length, leads to increasing pull-out capacity [12]. Increasing the groove dimensions, increasing the width-to-depth ratio of the groove, and using stiffer epoxy adhesive cause an increase in the bond strength. Moreover, using an edge distance of about twice the size of the groove for square grooves, results in no reduction in the bond strength [13]. The NSM FRP method shows bond behaviour superior to that of the EB FRP method, which has led to greater utilization of NSM FRP than EB FRP [14].

On the other hand, few investigations have been published on the bond between FRP-cement adhesive and the concrete substrate under monotonic loading using NSM pull-out tests [15–18]. The ultimate pull-out load of NSM specimens with cement mortar is less than that of NSM specimens with epoxy adhesive, because of the low tensile strength of cement mortar compared to that of epoxy adhesive [15]. NSM specimens using epoxy adhesive showed an ultimate pull-out capacity of about twice that of their counterpart specimens using polymer cement adhesive. Moreover, increasing the size of the NSM groove did not have an important effect on ultimate pull-out capacity for epoxy adhesive-specimens, while it led to a decrease in the ultimate pull-out capacity of polymer cement adhesive-specimens [16]. The ultimate pull-out load of specimens with epoxy adhesive was nearly double that of their counterpart specimens with cement mortar [17]. The polymer cement adhesive can be used within a pot life of about 20 mins only for NSM FRP applications [18].

Although the NSM FRP system using organic adhesives (epoxy adhesives) shows a suitable bond between the FRP, the organic adhesive and the concrete substrate, the use of epoxy adhesive with NSM FRP and EB FRP strengthening method has major problems, due to the release of toxic fumes throughout curing, and these adhesives are highly flammable [2]. Moreover, when exposed to temperatures above 70 °C, polymer-based adhesive loses its properties [19]. In addition, it has low permeability and weakness to UV radiation [20]. Furthermore, it has limitations in the work environment on site, such as being impossible to use on humid surfaces and at temperatures less than 10 °C [2,21].

To avoid these drawbacks of epoxy adhesive, several researchers have used composite systems having FRP materials with cementitious-based agents [22,23]. The research shows that the use of polymer cementitious mortars [22] to bond FRP materials to the concrete substrate using NSM systems can improve the ultimate bearing capacity better than non-polymer cementitious agents [23]. However, polymer cementitious mortars are affected by hydrothermal conditions [24–26]. Therefore, it is necessary to fabricate a high-strength non-polymer cement-based bonding material able to improve the strengthening capacity of RC structures using FRP materials, by enhancing the bond between the concrete substrate and cement-based adhesive and FRP material, in order to sustain structural integrity under harsh environmental conditions.

In a previous work by Mohammed et al. 2016 [27], the authors report the development of an innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA), which has 28-day tensile strength and compressive strength of 13.8 MPa and 101 MPa, respectively. This high mechanical strength is believed to be the key factor in the development of high strength in NSM FRP repair and strengthening systems. Graphene oxide (GO), one of the most commonly used derivatives of graphene, is used to synthesise IHSSC-CA. The improvement of the ductility of strengthened and/or repaired RC structures using FRP materials is an important safety concern, since structures strengthened and/or repaired using epoxy and polymer cementitious adhesives to bond FRP to concrete substrate have low ductility, which may cause sudden failure without warning.

The bond between the FRP, the adhesive material and the concrete is vital for a successful NSM FRP strengthening system. Therefore, the bond between CFRP strips, adhesive and the concrete was investigated in this work. A total of 18 NSM pull-out specimens were tested using epoxy adhesive, polymer cement-based adhesive and innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA). Also, analytical model to predict the ultimate pull-out force (bond strength) is proposed.

The aim of this research is to provide experimental evidence on the effectiveness of the use of IHSSC-CA with the NSM FRP system and the ability to use it in situ. Therefore, a durable, compatible and more efficient NSM method using CFRP strips with IHSSC-CA is proposed to enable application in the working environment on site for the rehabilitation of RC buildings and bridges. The development of durable NSM CFRP systems can extend the service life of rehabilitated infrastructures, reduce maintenance costs and guarantee people's safety.

2. Experimental work

2.1. Specimen details

The details of the pull-out specimen are shown in Fig. 1. The dimensions of each specimen were 75 mm (thickness), 75 mm (width) and 250 mm (length). In the pull-out specimens, the groove sizes equal to 5×30 mm (Fig. 1). The size of the grooves was determined in order to be consistent with ACI 440.2R-08 [28]. To enable load application, the CFRP strip was extended with at least 100 mm outside the concrete prism and attached with two aluminium plates with a dimension of $50 \times 50 \times 2$ mm at the loaded-end of each CFRP strips (Fig. 1).

Eighteen specimens were manufactured and tested. The test variable was the adhesive type (innovative non-polymer cement-based (IHSSC-CA), polymer cement-based and epoxy adhesives). Three series were tested and each series consisted of six specimens, three without strain gauges and three with strain gauges, as shown in Table 1. The first letter of the sample "M" means monotonic pull-out test; "IC" refers to innovative non-polymer cement-based adhesive (IHSSC-CA), "C" refers to polymer cement-based adhesive and "E" refers to epoxy adhesive; and "SG" means specimens with strain gauges.

2.2. Materials

Normal strength concrete was design based on ACI 211.1-91 [29] to cast all the pull-out specimens. The mix ratios were