Assessing the effectiveness of cementitious adhesive made with graphene oxide in NSM CFRP applications

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ABSTRACT: Efficient transfer of load between concrete substrate and fibre reinforced polymer (FRP) by the bonding agent is the key factor in any FRP strengthening system. An innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA) was recently developed by the authors and has been used in a number of studies. Graphene oxide and cementitious materials are used to synthesise the new adhesive. The successful implementation of IHSSC-CA significantly increases carbon FRP (CFRP) strip utilization and the load-bearing capacity of the near-surface mounted (NSM) CFRP strengthening system. A number of tests were used to inspect the interfacial zone in the bonding area of NSM CFRP strips, including physical examination, pore structure analysis, and three-dimensional laser profilometery analysis. It was deduced from the physical inspection of NSM CFRP specimens made with IHSSC-CA that a smooth surface for load transfer was found in the CFRP strip without stress concentrations in some local regions. A smooth surface of the adhesive layer is very important for preventing localized brittle failure in the concrete. The pore structure analysis also confirmed that IHSSC-CA has better composite action between NSM CFRP strips and concrete substrate than other adhesives, resulting in the NSM CFRP specimens made with IHSSC-CA sustaining a greater load. Finally, the results of three-dimensional laser profilometery revealed a greater degree of roughness and less deformation on the surface of the CFRP strip when IHSSC-CA was used compared to other adhesives.

1 INTRODUCTION

Two-component epoxy resin organic adhesives are most frequently used for adhering FRP to reinforced concrete (RC) structural members, as the adhesive has a key role in any strengthening technique for RC structures. However, the use of these adhesives with strengthening techniques for RC structures has significant drawbacks because of the release of toxic fumes during curing, which may cause irritation and eczema to human skin. In addition, this type of organic adhesive is highly flammable (Täljsten and Blanksvärd 2007). Furthermore, at temperatures above 70°C, polymer-based adhesive loses its properties (Gamage et al. 2006). Therefore, cement-based adhesives may be suitable alternative adhesive materials, since they have sufficient bonding properties (Hashemi and Al-Mahaidi 2012; Al-Saadi et al. 2016). However, polymer is still used as a major component in most cement-based adhesives. Recently, an innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA) has been developed and used in the fabrication of many NSM-CFRP strengthened specimens. Specimens have been tested under different conditions: fire, static and fatigue loading. The results show significant enhancement of the performance of specimens (Mohammed et al. 2016; Al-Saadi et al. 2017; Al-

Saadi et al. 2017) compared with similar specimens fabricated with epoxy or other polymer-cement-based adhesive. It is believed that the reason for these results is the sufficient load transfer in the bonding area, as IHSSC-CA maintains adequate load transfer on the surfaces of the CFRP strips, which results in increased load capacity and for other samples increased fatigue service life. The present research aims to shed light on why the use of IHSSC-CA results in a successful strengthening system. The research examines the bond zone in contact with the CFRP strip. Study of the bond zone is very important in providing a better understanding of the performance of strengthened specimens. It helps to explain both the weaknesses and strengths in order to overcome the defects and/or improve the strengths.

2 EXPERIMENTAL WORK

Nine concrete prisms 75 x 75 x 250 mm were prepared for direct pull-out tests using different adhesives (IHSSC-CA, polymer cement and epoxy adhesives) and three NSM specimens were tested for each type of adhesive. A normal-strength concrete was used to cast the prisms. The mix design proportions by weight were according to ACI 211.1-91, and the concrete prisms were ready for making the grooves after 28 days moist curing. A table-mounted saw was used to cut a groove 5 x 30 mm suitable for placing a CFRP strip with a size of 1.4 x 20 mm, according to ACI 440.2R-08. More details of specimen preparation can be found in Mohammed et al. (2016). The IHSSC-CA was prepared using an automatic mortar mixer according to the BS EN 196-1, BS EN 196-3, BS EN 480-1 specifications. At the beginning, the dry materials were mixed for 2 minutes at high speed. Next, graphene oxide (GO) was added, followed by the mixing water and super-plasticizer. The CFRP laminate was cut to the required size and 50 mm was left unbonded at the loaded end to avoid specimen edge failure. Prior to applying the adhesive, the groove was wetted with water. Then, the groove was filled with IHSSC-CA using an injection gun. Next, the CFRP strip was inserted into the groove to the required depth. Finally, any excess adhesive was removed and the surface of the concrete prism was levelled. Owing to the high fluidity and self-consolidation of IHSSC-CA, ease of application was highly satisfactory. In addition, the self-consolidation property of IHSSC-CA avoids the formation of air voids inside the groove which may affect the bond between the CFRP strip and the concrete surface. Other adhesives used for comparison purposes were polymer-based cement adhesive (PCA) and epoxy to fabricate the specimens for the pull-out tests.

3 RESULTS AND DISCUSSION

The average value of three specimens was considered as the bond characteristic of the NSM CFRP specimens. The results of pull-out tests showed a comparable pull-out load for the specimens with IHSSC-CA of 34.53 KN as the epoxy specimens showed a load 41.08 KN. This result indicates the superior ability of IHSSC-CA to sustain the applied load and at the same time overcome the drawbacks of epoxy. The test results for the specimens with PCA showed a pull-out load 22.25 KN, which is around 50% that of the epoxy specimens.

3.1 *Physical inspection*

Valuable information on the reasons for the significant bond strength was derived from the physical examination of the bond area after the pull-out tests. Figure 1 shows images of the physical inspection of the CFRP strips used in the pull-out tests for samples with IHSSC-CA, PCA and epoxy. It can be seen from Figure 1 (a) that IHSSC-CA effectively encapsulates the CFRP strip along the bond length where the CFRP strip is completely covered by IHSSC-CA. It can be concluded that, due to the liquid-like nature of IHSSC-CA, it fully and equally coats the

CFRP strip and maintains a sufficient surface area of adhesive in the bond area. In addition, the self-compacting characteristic of IHSSC-CA works to eliminate the creation of air voids during the pouring of adhesive into the groove. These physical properties of high fluidity and zero compaction have been shown to be important for the development of considerable bond strength. Figure 1 (b) shows a sample with polymer based-cement adhesive, and it can be seen that there are many defects in the adhesive layer along the surface of the groove. Theses defects may be created due to difficulty in consolidating the adhesive layer during the application process. As a result, air voids were created and caused non-uniform settlement of the adhesive layer. It can be deduced that due to the addition of polymer in the cementitious mixture, the fluidity of the adhesive and pot life was reduced and this reduced the ease of application of the adhesive layer uniformly and evenly. Furthermore, in Figure 1 (c) showing the CFRP strip with epoxy, it can be seen that the use of high-viscosity adhesive such as epoxy causes difficulty in maintaining a uniform thin layer of adhesive. It is clear that a uniform thin layer of adhesive was not initiated due to the high viscosity of the epoxy and low pot life, which make it difficult to obtain an even distribution of the adhesive layer on the attached surfaces. As a result, this uneven layer of epoxy created a weak bond zone with many defects. In addition, it can be concluded that the areas on the attached surfaces with more adhesive created regions for stress concentration and subsequently caused sudden failure of the tested samples. Many parts of the concrete substrate with gravel particles attached on the surface of the CFRP strip were observed, as shown in Figure 1 (c). This shows that localized stress concentration occurred in these regions and caused brittle failure of the concrete substrate.

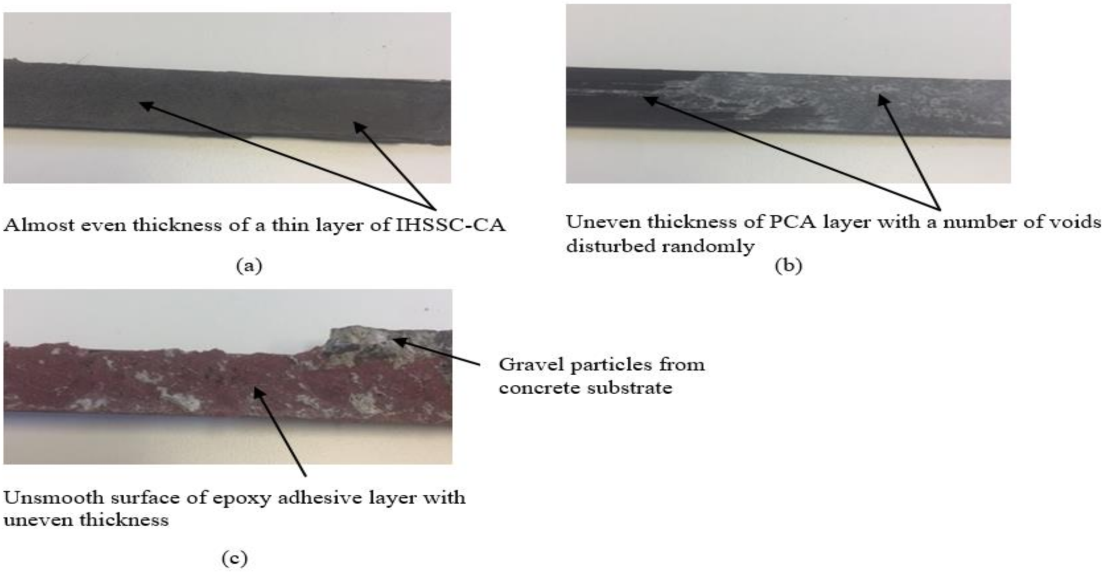

Figure 1. Images of bond area after testing.

3.2 *Pore structure analyses*

The Burnauer-Emmett-Teller (BET) isotherm analysis is frequently used to study the adsorption properties of many types of materials (De Belie et al. 2010). In the present research, nitrogen adsorption isotherms were used to investigate the pore structure of the adhesives before and after pull-out testing. The results can be used to infer the contribution of adhesives to the NSM CFRP strengthening technique in resisting applied load. The adhesives were IHSSC-CA and polymer cement-based adhesive (PCA). It is not appropriate to conduct this test for epoxy adhesive because epoxy has very low permeability, which makes it unsuitable for nitrogen adsorption testing. A Bell nitrogen adsorption machine was used for the tests at an adsorption temperature of 77 K. Figure 2 shows the nitrogen adsorption isotherms for unloaded IHSSC-CA and after applying the pull-out test. It can be seen from Figure 2 that IHSSC-CA shows greater adsorption after the pull-out test than the unloaded IHSSC-CA, with more pronounced hysteresis loops. This observation indicates that the IHSSC-CA of the NSM specimens experienced more damage in the microstructure during loading. This reflects the great contribution of IHSSC-CA to transferring the applied loads. Figure 3 shows the nitrogen adsorption isotherms for unloaded PCA and after applying the pull-out test. In contrast, the adsorption isothermal curves of PCA show slight change in adsorption of this adhesive, which means little damage to the microstructure during loading. Therefore, it can be deduced that PCA makes lower contribution to transferring the applied load.

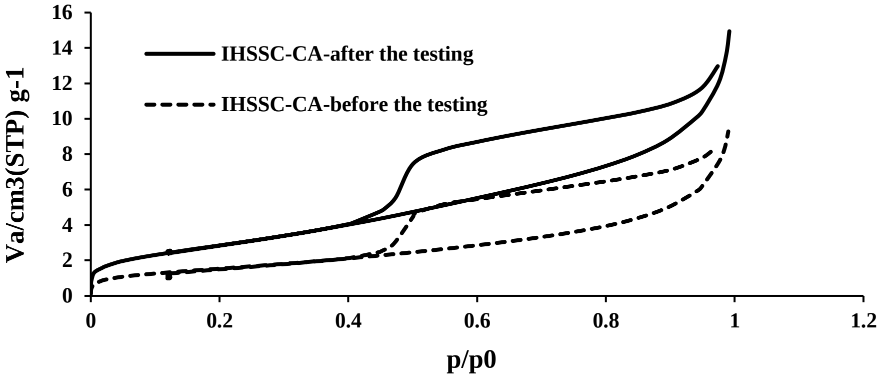

Figure 2. Nitrogen adsorption isotherms for IHSSC-CA.

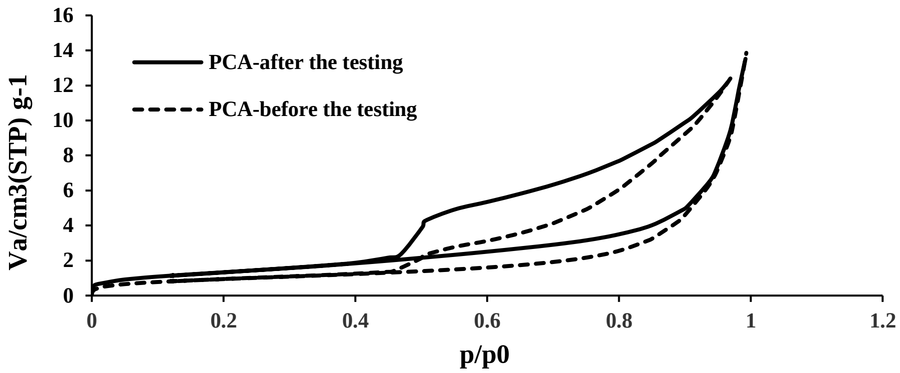

Figure 3. Nitrogen adsorption isotherms for PCA.

3.3 *Three-dimensional laser profilometery analyses*

A 3-dimensional (3-D) laser interferometry was used to investigate the topography (roughness) of the CFRP strip before and after pull-out testing. It is of great importance to measure and characterise the topography of the CFRP strips for evaluating the adequacy and efficiency of the bonding system. Samples of CFRP strips were collected from similar positions around the mid-span of the CFRP strips of the tested specimens; the length of samples tested was about 18 cm. The samples were cleaned thoroughly before placing in the profilemetry machine. 3-D micrographs of the CFRP strips were taken using a Bruker vertical scanning interferometer (Nanotech Photomap 3D), as shown in Figure 4.

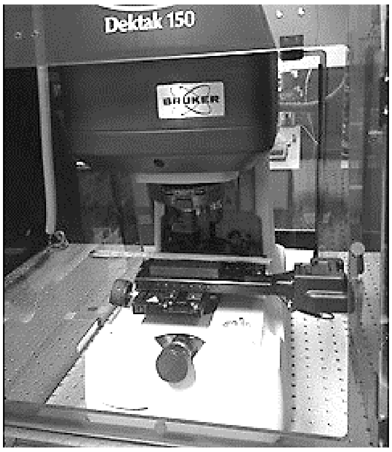

Figure 4. Laser profilometery for CFRP surface after failure analysis.

The roughness parameters were micro surface roughness (Ra), which represents average roughness; root mean average (Rq); Rt, the peak-to-valley difference; and Rv, the maximum profile valley depth. These values were calculated using Veeco 3-Dimensional software in accordance with ANSI B46.1. The 3-D analyses of the captured images were constructed with the same software. The roughness values were then used to explain the utilization of the CFRP strips (Santos et al. (2007); Santos et al. (2013)). The nature of the CFRP strip-adhesive bond can be effective in both decreasing and increasing the overall mechanical and durability performance of strengthening systems (Hola et al. (2015). In particular, the first layer of adhesive that contacts the CFRP strip has special importance in developing a sufficiently strong bond, as a dense and uniform adhesive layer can result in greater strength development in strengthening systems (Erdem et al. (2013). On the other hand, an adhesive layer containing severe defects will rapidly degrade and lose load capacity (Hola et al. 2015). The surface texture or roughness in this zone is a result of the mechanical response of the solid material (CFRP strip) which reveals morphological differences in the corresponding failure (Ficker et al. 2010). Figure 5 shows 3-D and 2-D images of a plain CFRP strip, and the 2-D woven textile of the strip is clearly observed. Table 1 shows the roughness parameters of the plain CFRP strip and the CFRP strips with different adhesives after application of the load.

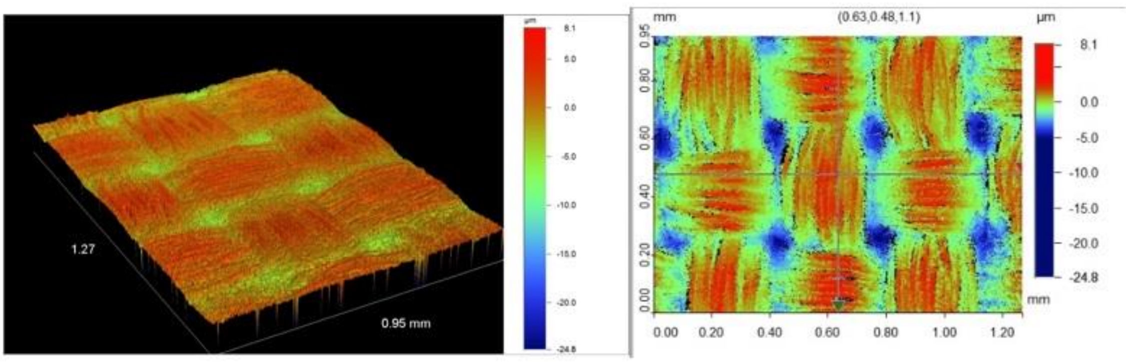

Figure 5. 3-D and 2-D images of topographic surface of plain CFRP strip.

Table 1. Roughness parameters (µm) of plain CFRP strip and CFRP strips with different adhesives after application of load.

Specimen	Ra	Rq	Rt	Rv
Plain CFRP strip	1.32	1.73	44.56	38.07
CFRP strip with IHSSC-CA	11.44	13.62	81.52	74.51
CFRP strip with PCA	8.65	10.72	67.46	65.47
CFRP strip with epoxy	9.94	12.17	77.6	61.84

Examination of the surface of the plain CFRP strip was used as a reference to compare it with surface differences after application of the load. The analysis revealed a clear difference in the surface roughness characteristics of the CFRP strips after applying load. Figures 6,7 and 8 show the CFRP strip after applying the pull-out load for the specimens strengthened with IHSSC-CA, PCA and epoxy respectively. It can be deduced from these figures and from the roughness values shown in Table 1 that the roughness of the CFRP was greater when IHSSC-CA was used compared to other adhesives. This can be attributed to the formation of a uniform adhesive layer, which was able to successfully distribute the applied stress uniformly and stimulate more threads of the CFRP strip to resist the applied load. Another important factor that can be considered is the better interlocking of IHSSC-CA with the threads of CFRP strip due to the high fluidity of IHSSC-CA. As a result, the Rt (81.52 µm) and Rv (74.51 µm) values were higher than those for the other adhesives. This is also shown in the surface of the CFRP strip in Figure 6, where there was a uniform deformation of the woven threads of the CFRP strip, which shows that almost every individual thread of the CFRP strip was affected by the applied load . On the other hand, the deformation in the surface of the CFRP strip with PCA and epoxy was severe and not uniform. This non-uniform deformation in the surface of the CFRP strip may be caused by uneven distribution of the adhesive (PCA and epoxy) on the surface of the CFRP strip. In addition, to weak interlocking effect between the PCA and epoxy adhesives and the threads of the CFRP strip because high viscosity of the polymer which is a base component of both PCA and epoxy.

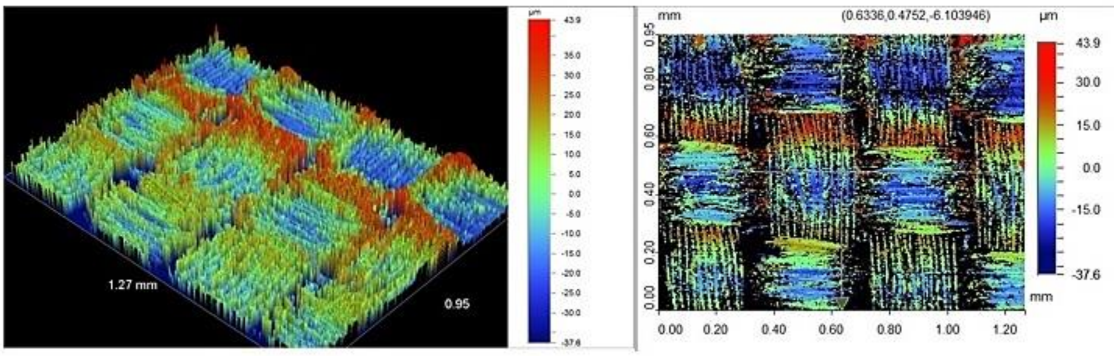

Figure 6. 3-D and 2-D images of topographic surface of CFRP strip with IHSSC-CA.

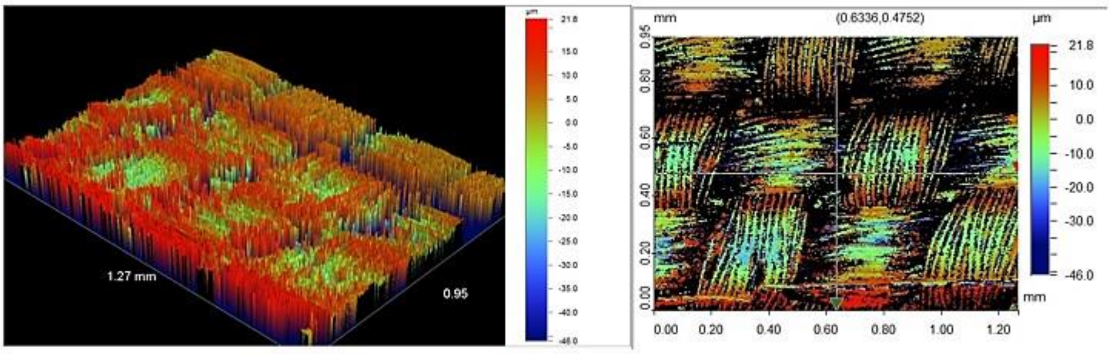

Figure7. 3-D and 2-D images of topographic surface of CFRP strip with PCA.

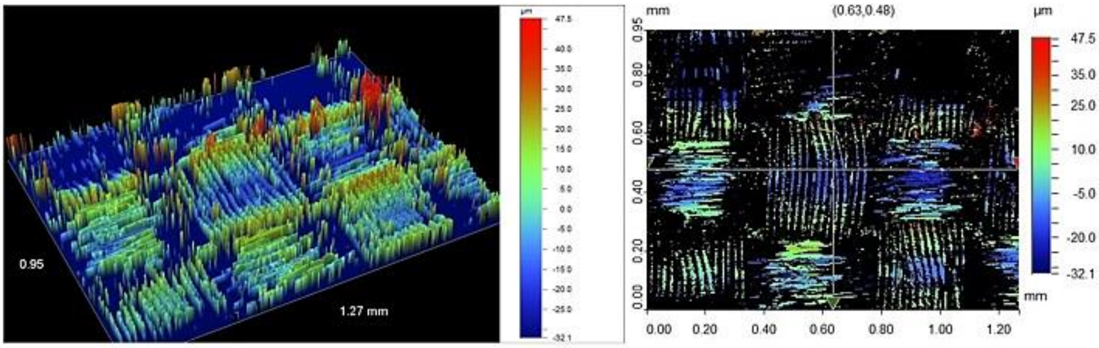

Figure 8. 3-D and 2-D images of topographic surface of CFRP strip with epoxy.

4 CONCLUSION

Several tests were conducted on CFRP strips after direct pull-out tests to investigate the effects of bond system properties. All the results from the investigation show high agreement with those of the pull-out tests. Physical investigation of the CFRP strips showed the effectiveness of obtaining a thin uniform adhesive layer that is able to transfer the applied loads efficiently by using IHSSC-CA and prevent the formation of stress concentration regions such as those formed in epoxy and PCA. In addition, pore structure analysis showed considrable change in the pore structure of IHSSC-CA after pull-out loading which showed a good response to the applied load. In contrast, PCA showed lower response to the applied load representive by low modification in the pore structure of this adhesive. Finally, the results of 3-D laser profilometery showed a high degree of roughness and less deformation in the surface of the CFRP strip when IHSSC-CA was used compared to epoxy and PCA adhesives. It can be concluded that IHSSC-CA can be used as an alternative to epoxy adhesive, since it provides high strength and it can withstand harsh environments.

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