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REVIEW RESEARCH

A REVIEW ON BOND PERFORMANCE OF FRP-CONCRETE SYSTEM AT VARIOUS ENVIRONMENTAL CONDITIONS

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Abstract Strengthening concrete structures with Fibre Reinforced Polymer (FRP) is one of the most commonly used technique to repair and rehabilitate concrete members due to the advanced properties of FRP over other conventional materials such as steel plates. The required performance of FRP-concrete system is linked to achieve proper bond between FRP and concrete substrates that as exposed to different environmental conditions. In the current paper, a review is conducted to highlight the most reported work by other researchers regarding the bond behavior of concrete members that strengthened with FRP in shear-tension and exposed to temperature-based conditions and compared with ambient conditions. The current review focused on the conducted work on FRP/concrete system that strengthened with two different installation techniques (externally bonding (ES) and near–Surface mounted (NSM)) using two different bonding agents (epoxy-based adhesive (EBA) and cement-based adhesive (CBA)) with and without modification. The adoption of two specific bond test procedures (adhesion and single lap shear tests) at ambient conditions and temperature-based conditions was also reviewed intensively to clarify the advantages and drawbacks that associated with each test. Some reported findings by others in conducting bond test methods for different FRP/concrete systems was highlighted as well to address the gap in knowledge and the need for further research in this regard.

Keywords: *Bond; FRP; concrete; adhesive; temperature*

1. Introduction

Retrofitting and strengthening concrete structures with Fibre Reinforced Polymer (FRP) presents the most preferable strengthening technique due to the numerous advantages of FRP [1-3] over other traditional materials such as steel plates [4,5]. Different types of FRP are utilized in the strengthening [6-8] and variety of FRP installation techniques [9] are exist and the two most popular FRP strengthening systems are externally bonded (ES) and near–surface mounted (NSM) strengthening techniques. ES is the more utilized method due to its practicality to strengthen different shapes and sizes of concrete structures [10-13]. Epoxy-based adhesive (EBA) is the commonly used bonding agent in ES technique. It addition to its toxic fumes and flammability, EBA is more sensitive to elevated temperatures that close to or exceeding its glass transition temperature (T_g) which presents the region where the deformation of the epoxy from unrelaxed (glassy) to relaxed (rubber) happed and measures the mobility of the molecular chains in the polymer network as function of temperature [14]. The other installation technique for FRP is NSM technique which also used for various strengthening forms [15-19]. EBA or cement-based adhesive (CBA) were utilized to work as bonding agent between FRP and concrete [20-22].

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The required performance of FRP/concrete system is connected to proper bond between FRP and concrete. Many parameters affect the bond effectiveness between FRP and concrete [23]. For ES FRP strengthening system, some parameters are related to the type and properties of materials that used in the strengthening system such as concrete, FRP and bonding agent. Concrete surface preparation also influence the effectiveness of bond in FRP/concrete system. Excessive work was conducted by researchers to zoom on the effect of each of the above factors on bond performance in FRP/concrete system [24-27]. For NSM FRP strengthening system, the same above factors also affect the bond between FRP and concrete in addition to the dimensions of the groove and its degree of roughness when EBA was used [28,29] and when CBA was used [30].

Another important factor affects significantly on the bond in FRP/concrete strengthening system when used for outdoor applications is service conditions. Regardless of FRP installation method and for FRP/concrete system using EBA, as the system exposed to temperature closes to or exceeds T_g of EBA, then loss of the bond between FRP and concrete occurs. This is due to degradation in the properties (reduction in strength and stiffness) of the bonding agent by such exposure temperature which increases the mobility of the molecular of the EBA for short-term exposure, but the adhesive and cohesive bond of EBA was found to be reduced as the service temperature increases for long-term exposure to harsh service temperatures [31]. In the current paper, selected work by other researchers on evaluation bond in FRP/concrete system subjected to temperature-based conditions using adhesion (pull-off) and single-lap shear tests was reviewed and compared with ambient conditions. The effect of these environmental conditions were chosen among other conditions since temperature is one of the most common and unavoidable environmental factor as outdoor structures are exposed daily. Some significant findings by others were reviewed as well in adopting different test configurations and arrangements to evaluate the bond of FRP/concrete systems that prepared using ES and NSM installation techniques and different bonding agents (EBA and CBA) with and without modification. This is to address the major advantages and disadvantages for the above bond tests and also to highlight the important differences in conducting bond efficiency experimentally using such FRP strengthening systems to identify the gap in knowledge and need for future investigations.

2. Bond Evaluation by Direct Tension (Pull-off) Test at Ambient Conditions Vs. at Temperature-Based Conditions

2.1 Test Configurations

The adhesion (pull-off) test in ASTM D4541 [32] was basically designed for evaluation the strength of adhesion between substrate and coating but it may use for evaluating adhesion strength of ES FRP-concrete system. The principles of this test is based on isolating the bonded area in FRP/concrete sample by making a groove around that area and then a loading fixture (i.e dolly) that made from steel plate is attached to the bonding area using thermoset epoxy adhesive of ambient temperature curing with properties that suits the testing conditions (Fig.1) [33].

Figure 1. Adhesion pull-off test at ambient conditions for ES FRP/concrete system using EBA [33]

Regardless of its simplicity and low-cost, some disadvantages are associated when adhesion test is adopted to evaluate the bond in ES FRP/concrete system if a comparison is to be made between the application of this test in laboratory and in the actual site. Some of these drawbacks were related to the variations in the obtained results due to the small scale specimens and localized nature of the test. Additionally the results in laboratory could not provide adequate evaluation about the bond in site as the FRP/concrete system for outdoor structures are not expose to direct tension. It was recommended to use the adhesion test as a quality control and baseline and further supplementary tests such as acoustic sounding are recommended to be used if adhesion test to be adopted [34]. In order to overcome some of the drawbacks of adhesion test, an attempt was reported by researchers to develop a non-destructive (ND) pull-off test (Fig.2). The modified test involves no drilling to isolate the tested area of CFRP/concrete sample and to allow the measurements of the displacement at the same time [35].

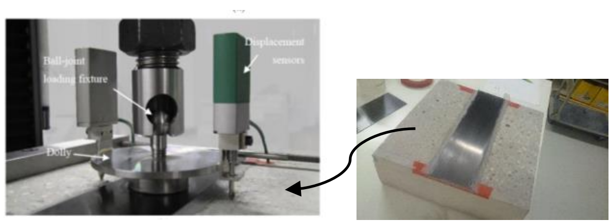


Figure 2. Developed non-destractive pull-off tester [35]

In regard to adhesion test at elevated temperatures, special arrangements should be considered. A reported work at moderate elevated temperatures [36] conducted this test by placing cubic samples of CFRP/concrete using EBA to be fit in steel frame. Aluminum disc was used instead of the dolly that used at ambient conditions to be glued to the isolated area on CFRP/concrete samples by using epoxy adhesive of high temperature resistance properties. This is to avoid bonding epoxy failure at loading fixture. The set-up was placed inside test chamber and connected to loading machine (Fig.3). A sustained load was applied to CFRP/concrete specimens prior to the gradual increment in the temperature till losing the bond.

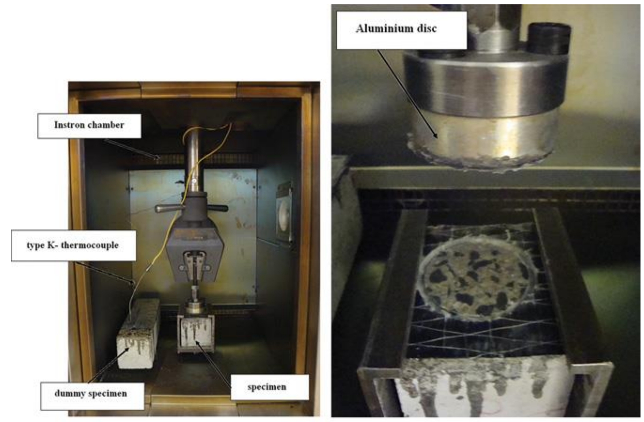


Figure 3. Arrangments for adhesion test at moderate elevated temperatures for ES FRP/concrete system using EBA [36]

2.2 Failure Patterns

Different patterns of failure (mode A - mode G) may occurred (Fig.4) as adhesion (pull-off) test is conducted. Mode A presents bonding epoxy failure at dolly. Mode B refers to cohesive failure in FRP laminate. Modes D presents failure in epoxy. Mode G refers to cohesive failure in in concrete. Modes C and E present epoxy failure in interfaces (FRP/epoxy and epoxy/concrete interfaces respectively). A combination of failures may occur as well as in Mode F in which the failure is mixed of cohesive failure in concrete and epoxy at the interface of epoxy/concrete [37].

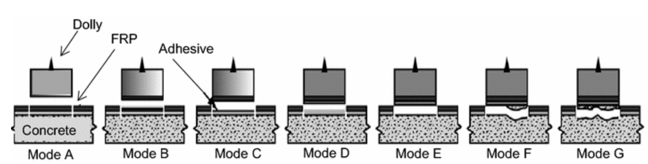
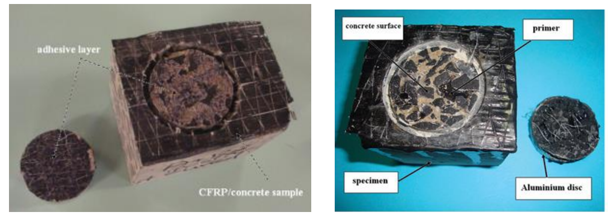


Figure 4. Failure patterns in accordance to ASTM D7522/D7522M [37]

Concrete rupture was reported as the common failure mode from testing concrete samples that strengthened externally with one layer of CFRP sheet using commercially EBA of ambient temperature curing (Fig.5) [33]. This means proper bonding (adhesion strength) between FRP and concrete. Similar failure mode was also observed in another laboratory investigation [38].

Figure 5. Failure mode of CFRP/concrete system at ambient conditions [33]

In terms of test at elevated temperatures, cohesive failure in the adhesive that bond CFRP sheets to concrete was reported [36]. This was attributed to the reduction in the properties (T_g and modulus) of the EBA between CFRP and concrete as the test temperature exceed the T_g of the commercial EBA. Similar failure pattern (Fig.6a) was reported when the same previous EBA was modified with different concentrations of nanoclay [38]. However, the failure mode was in the primer/concrete interface when EBA was modified with vapour-grown carbon nanofibre (VGCF) in CFRP/concrete samples (Fig.6b) [36]. Failure in the primer/concrete interface (Fig.7) was reported also by another study for CFRP/concrete system using modified high-functionality resin (DGOA) with 1wt% and 2wt% of VGCF. Such mode of failure was attributed to the lower adhesion strength between concrete and the primer than the cohesion strength [39].



(a) (b)

Figure 6. Failure mode of ES CFRP/concrete system at elevated temperatures using commercially EBA-modified with (a) nanoclay [38], and (b) VGCF [36]

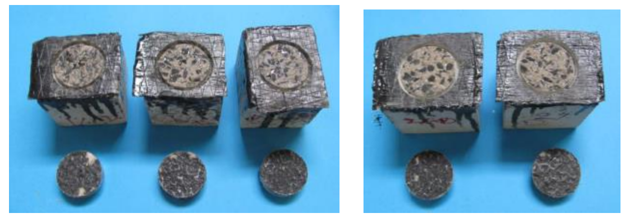


Figure 7. Failure mode of ES CFRP/concrete system at elevated temperatures using VGCF–modified DGOA [39]

2.3. Bond-Loss Temperature

Limited literatures were addressed to evaluate the bond by direct adhesion (pull-off) test at elevated or high temperatures with load applications. The available data was reported in two experimental work about the bond-loss temperature of 60°C for CFRP/concrete samples using commercial EBA of 70°C for T_g and loaded with sustained load with gradual increment in temperature till failure. As the commercial bonding EBA was modified with VGCF, very slight enhancements (2-3°C) in the bond-loss temperature were reported in comparison with unmodified commercial EBA [36]. An enhancement of 7°C in the bond-loss temperature was reported by another study when CFRP sheets were glued to concrete using 2wt% of VGCF modified DGOA [39].

2.4. Residual Bond Strength

The FRP/concrete system in some studies was heated first for specific period and then the residual bond strength was obtained. Part of a reported experimental investigation was executed to study the effect of different exposure levels of temperature (80, 160 and 240°C) for two exposure periods (1.5 and 3 hrs) on the interfacial bond of ES CFRP/concrete system using modified EBA [40]. Normal strengths concrete (C30 and C50) were used to fabricate concrete samples which were strengthened with CFRP sheets using silica nano-powder-modified EBA.

Strengthened samples were first exposed to the above conditions in chamber without loading. All tested samples showed concrete rupture as a failure mode since this test was performed at ambient conditions. The residual bond strengths from testing control and heated samples were reduced the exposure temperature was increased with the increment in exposure time (Fig.8). Higher results were reported for samples that prepared with mix C50. The reduction in the bond strength was attributed to the formation of microcracks in concrete/EBA interface as the temperature was increased in addition the reduction in the confinement effect which causes an increment in the width of the cracks. Further degradation in the bond strength was occurred as the exposure temperature was increase with time. Additionally, pores and cracks are also formed in the concrete due to the evaporation of free water in concrete due to high temperature.

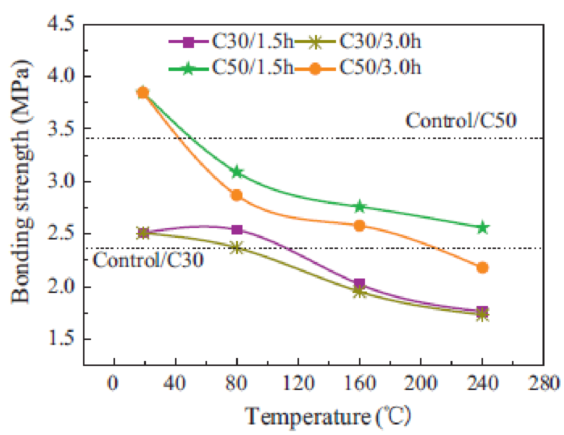
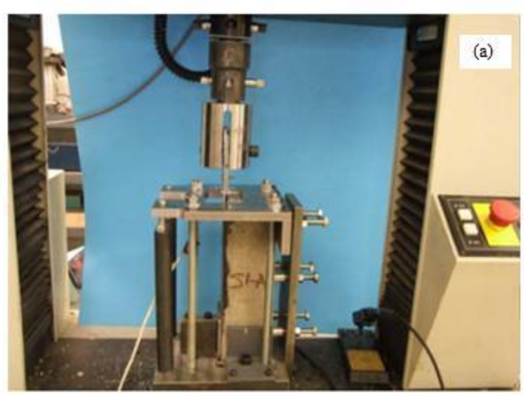


Figure 8. Adhesion test results for ES CFRP/concrete system using nanomaterials-modified EBA after exposure to hight tempeartures [40]

3. Bond Evaluation by Single-Lap Shear Test at Ambient Conditions Vs. at Temperature-Based Conditions

3.1 Test configurations

In ES FRP/concrete system, the fabrication of FRP/concrete sample for single-lap shear at ambient conditions involves the application of FRP (sheets, textile and laminates) on one side of prismatic concrete specimen. Prior to FRP application by wet-lay-up method, concrete surface is coated with thin layer primer of ambient temperature curing. In terms of NSM, a groove on concrete surface is made to insert FRP. For load application, for both techniques, the length of FRP is extended further than the bonded area. One of the advantages of using this test is the simplicity that associated with the preparation of the sample in which less FRP and concrete is used in comparison with other bond test methods. However, more complex details is needed to be taken into consideration to avoid the problem in the design of the set-up rig. The possibility of load eccentricity to occur on the concrete specimen is avoided by support the concrete sample on the top near the loaded end. An example of the single-lap shear test set-ups at ambient conditions is shown in Fig.10 for ES and NSM techniques [33, 41,42].



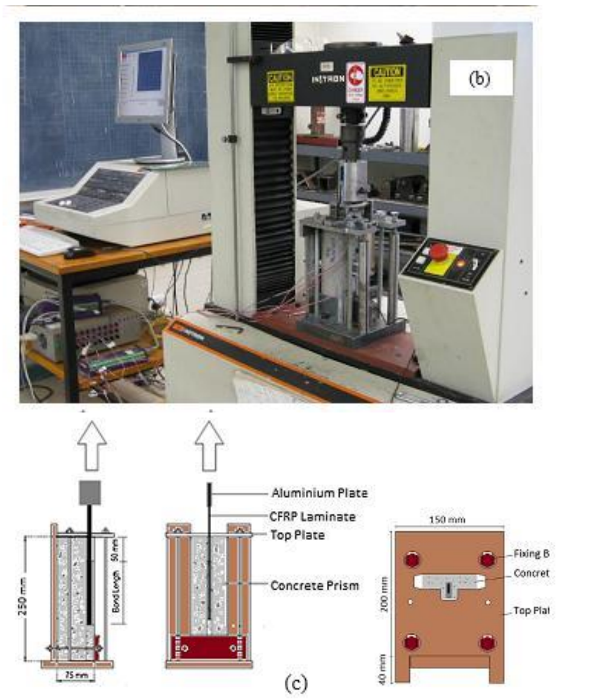


Figure 9. Different single-lap shear set-ups for : (a,b) ES FRP/concrete sysyems [33,41], and (c) NSM FRP/concrete system [42]

Regarding tests at temperature-based conditions, most of the reported experimental work addressed the need for more arrangements to conduct single-lap shear test at such conditions and for loaded samples. The set-up rig, made from a material can resist such conditions, is placed inside test chamber and connected to loading machine. In order to eliminate the influence of exposure temperature on the free end of FRP (unbonded FRP) that used for load applications during the exposure to such conditions, protection to that free end by using insulator was used. Some reported work addressed that the length of free end of FRP was extended further depending of the size of the test chamber. More protection in this case are needed to protect that extended length from the exposure conditions. In terms of fire, the front and/or side faces of loaded concrete samples were protected with mortar and gypsum board [43].An example of the reported test configurations by other researchers are shown in Fig.10-Fig.12. These for different FRP/concrete systems using EBA or CBA subjected to high temperatures [41,44] respectively and fire [43].

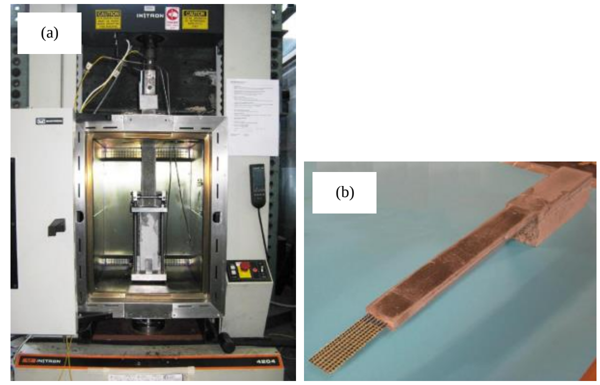


Figure 10. Single-lap shear test at high temperatures for ES CFRP/concrete using CBA: (a) Test configuration, and (b) sample [41]

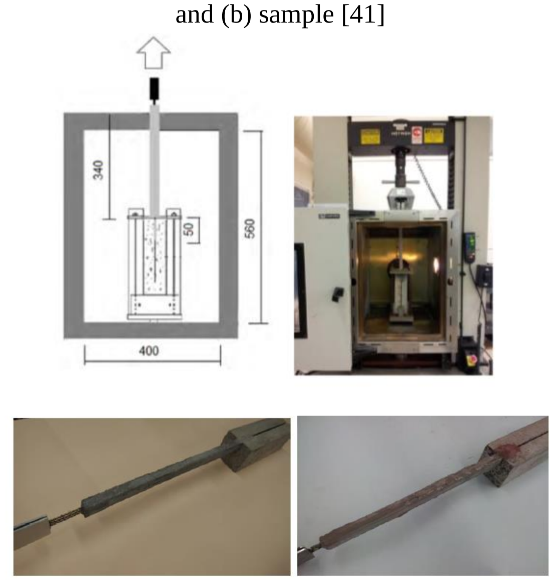


Figure 11. Single-lap shear test at high temperatures for NSM CFRP/concrete system using EBA and modified CBA : Test configuration (top), sample (bottom) [44]

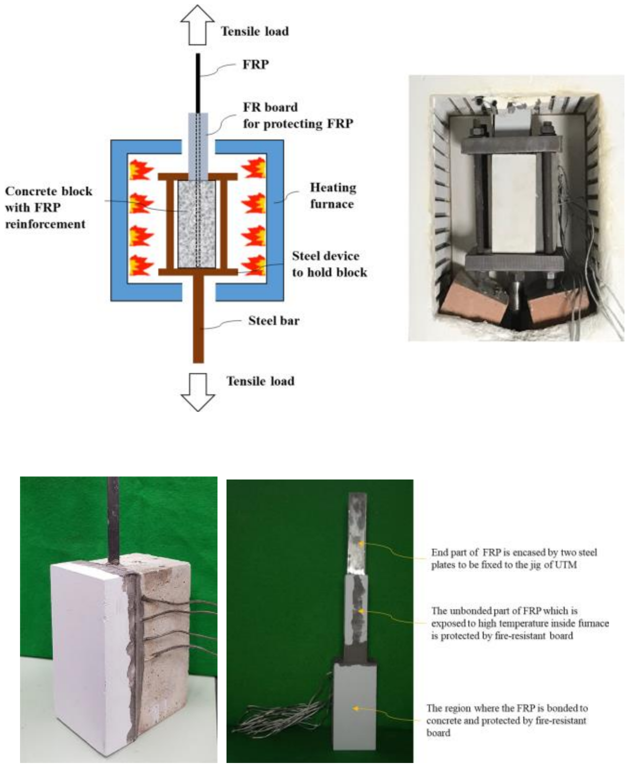


Figure 12. Single-lap shear test at fire conditions for ES FRP/concrete system using EBA: test configuration (top), sample (bottom) [43]

3.2 Failure patterns

3.2.1 ES FRP strengthening system

The most commonly failure patterns in conducting single-lap shear test using ES FRP strengthening technique are illustrated in Fig.13 [45]. It was reported that concrete rupture (Mode 1) is the most commonly failure mode as the test was conducted at ambient conditions [33,46]. Mode 2 occurs if FRP laminate is so thick and this failure is shear-tension failure as the crack starts in the concrete and forwards to the adhesive layer. Mode 3 presents the FRP tensile rupture. Mode 4 is cohesive failure in the adhesive. Mode 5 present FRP delamination in which the delamination may penetrates the adhesive layer and concrete.

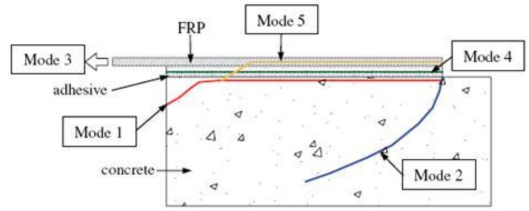


Figure 13. Failure patterns of ES FRP/concrete system tested by single-lap shear [45]

Depending on the method of development, various failure patterns were reported from testing CFRP/concrete system at ambient conditions using modified insulator adhesive [47]. It is an engineered cementitious composite (ECC) mortar adhesive made from cement, fly ash, silica sand, water and Polyethylene terephthalate (PET) fibres. The PET-ECC mortar adhesive was applied to bond CFRP sheets to concrete with a total thickness of 10mm. The modified PET-ECC was applied as 5mm on concrete surface then CFRP sheets were pressed on it then another 5mm of the adhesive was applied on the top of CFRP. Slurry of PET-ECC was used instead of mortar for some samples. River sand or silica sand was glued by epoxy to both sides of CFRP sheet prior to bonding it to concrete using PET-ECC adhesive to increase the energy of attachment in the interface. Regardless of the higher bond strength, failure in concrete/PET-ECC interface (Fig.14a) was recorded for samples using PET-ECC with river sand attached to CFRP. However, failure in CFRP/PET-ECC interface was recorded for samples using PET-ECC with silica sand attached to CFRP (Fig.14b) and for samples with PET-ECC slurry (Fig.14c).

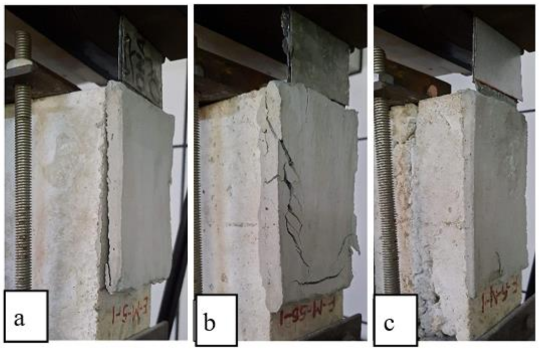
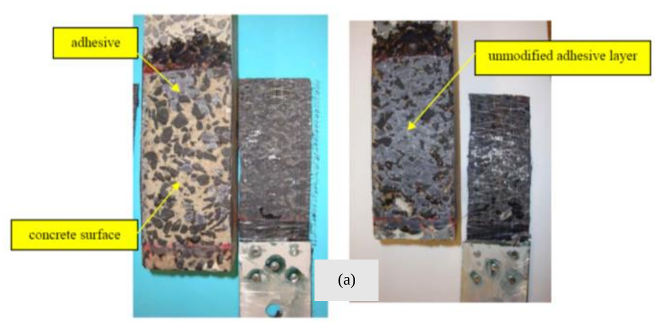


Figure 14. Failure patterns of ES FRP/concrete system tested using developed PET-ECC adhesives [47]

Another study reported that the failure mode was varied with the temperature range as ES CFRP/concrete samples were tested at temperatures ranging (25°C-140°C) using commercially EBA with T_g of 62°C. As the test temperature was in the range of 22 to 36°C, concrete rupture was noted as failure pattern. The adhesive failure was noted for samples that tested to elevated temperatures in the range of 50-70°C and peeling-off CFRP sheets was also reported for specimens as the exposure temperature was exceeded 60°C (Fig.15a). A combination of concrete rupture and adhesive failure was observed for samples that exposed to temperature less than 50°C (Fig.15b) [48].

Figure 15. Failure modes for ES CFRP/concrete system using EBA at elevated tempaertures [48]

The influence of post-curing on failure mode in FRP/concrete system that tested at moderate elevated temperatures was addressed by another group of researchers using two different procedures for test [49]. After fabrication of single-lap shear samples, CFRP/concrete specimens were left at ambient conditions for more than 7 days and then placed in an oven at 60°C for 4 hrs and then left at ambient conditions till testing. Two exposure programs were applied for testing at elevated temperatures. The first program was by loading post-cured samples with 40% of the ultimate load and then the temperature inside the test chamber was gradually increased till losing the bond. The second program involved exposing post-cured samples to constant temperatures and then the load was applied till losing the bond. Some samples were exposed to constant temperature (40°C) which is less than T_g of EBA and other samples were exposed to 60°C (closer to T_g). For constant loaded samples and tested at elevated temperatures, the failure for control specimens was in the EBA/CFRP interface while it was in the primer/concrete interface with some EBA parts were left on the surface of the concrete (Fig.16a). In terms of samples exposed to constant temperatures, the failure mode for samplers that tested at 40°C was concrete rupture for both control samples as well as post-cured samples (Fig.16b). Regarding samples tested at 60°C, control samples showed combination of failure patterns (cohesive failure in EBA in addition to failure in primer/concrete interface) while post-cured specimens showed failure in the primer/EBA interface which was attributed to lower cohesion strength between EBA and the primer (Fig.16c).



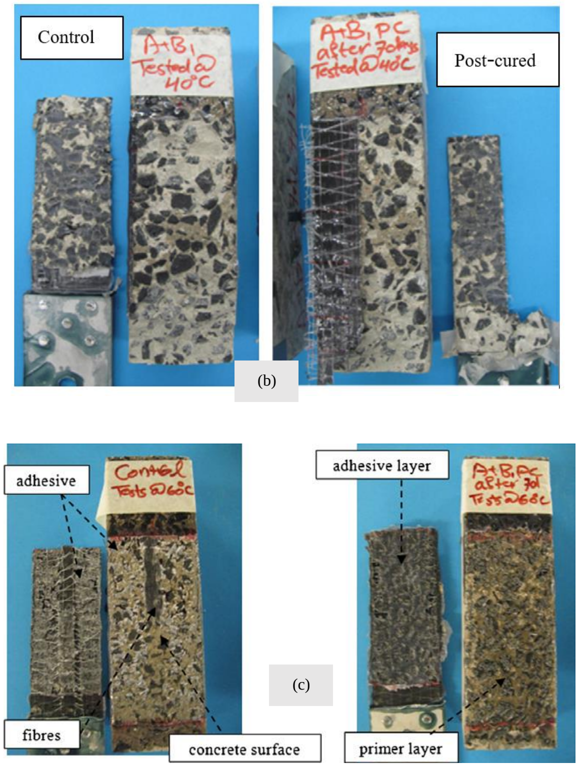


Figure 16. Failure modes for ES CFRP/concrete system using EBA with and without-post curing at 60°C and tested at: (a) moderate elevated tempertures and constant load, (b) 40°C and (c) 60°C [49]

Another investigation reported debonding of CFRP textile as loaded CFRP/concrete system was exposed to high temperatures. CFRP was placed on concrete surface with 20mm CBA overlay [41]. Gradual burning of epoxy from CFRP tows surface causes CFRP to shear-off from the overlay. Such failure was explained as CFRP losing the bond gradually at areas with higher bond stress and closer to the loading edge. Shear stress, after losing the bond, was transferred to adjacent area and then lost at the new area. This behavior was continued gradually till losing the bond at the end of CFRP was occurred.

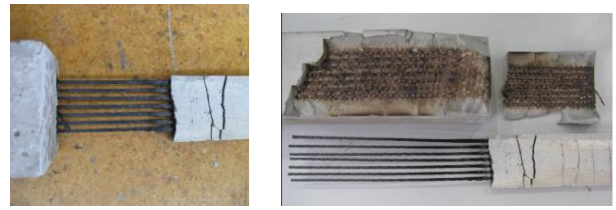


Figure 17. Failure mode for loaded ES CFRP/concrete system using CBA tested at high tempertures [41]

3.2.2 NSM FRP strengthening system

Various failure patterns were reported for NSM FRP/concrete system using modified CBA depending on FRP type and test conditions. An interfacial failure between CFRP textile and concrete was observed at ambient conditions. Longitudinal cracks were also noted in the adhesive (Fig.18a) [42]. The failure pattern was changed to carbon fibre slippage that affect the CBA layer. Cracks were observed in the CBA layer as the strengthen system was tested at high temperatures (Fig.18b). When CBA was replaced with EBA for the same system, the failure pattern was CFRP slippage with concrete rupture at the loaded end of the sample (Fig.18c) [44].

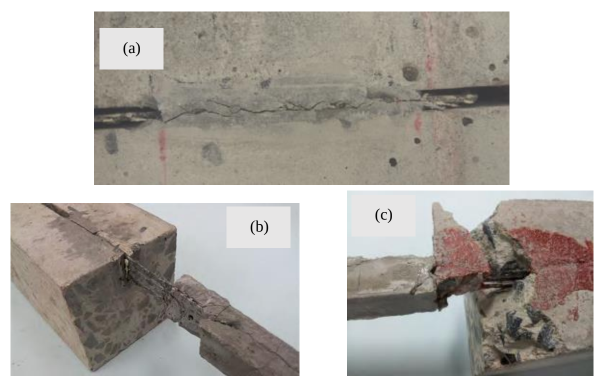


Figure 18. Failure patterns for NSM CFRP/concrete samples tested at: (a) ambient conditions using modified CBA [42], (b,c) high temperatures using modified CBA and EBA respectively [44]

The same NSM CFRP/concrete system using modified CBA and CFRP laminate was also tested in site to evaluate the adhesive performance on bond under harsh environmental conditions. Strengthened samples were loaded with the same manner that followed at laboratory via special springs (Fig.19a). The loaded samples were then placed in site and exposed to direct sun in high temperature environment during summer season in United Arab Emirates. Measurements were obtained for the temperature of CFRP and concrete surface during the exposure period at different locations. It was reported that all loaded samples were survived during the exposure time. After testing at ambient conditions, the failure was in adhesive/concrete interface with CFRP slippage (Fig. 19b). In regard to the recorded temperatures, it was reported that the temperature of concrete surface was high than surrounding air by 24% while the temperature of CFRP was lower than the concrete surface by 1.5-2°C [44].

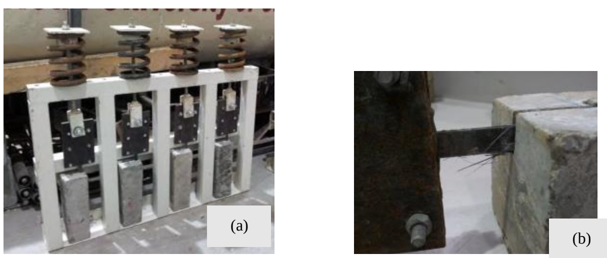


Figure 19. NSM CFRP/concrete system using modified CBA: (a) arrangement for applying sustained load, and (b) failure mode after exposure to site conditions [44]

3.3 Bond-Loss Temperature and Residual Bond Strength

3.3.1 ES FRP strengthening system

Reduction in the bond strength was reported from carrying out single-lap shear test at high temperatures on CFRP/concrete samples using commercially EBA with T_g of 58°C measured by Dynamic Mechanical Thermal Analysis (DMTA). The exposure program involved firstly, raising up the temperature of the CFRP/concrete specimens in the oven by 10°C for 15 mins then keep the temperature at 150°C for half an hour and then the load was applied till losing the bond. As the exposure temperature was in the range of 60°C and 70°C, rapid loss in the bond strength was reported (Fig.20a). For this strengthened system using such commercial EBA and based on the obtained experimental data, a relationship between the bond strength between CFRP and concrete with the temperature of EBA was proposed (Fig.20b). As the EBA temperature (T) was less than 45°C then the relative strength of CFRP/epoxy/concrete bond (ρ) is equal to (1). If T was greater than 45°C and less than 75°C, then ρ is equal to (2.0436–0.0236T). If T was greater than 75°C, then ρ is equal to (0.18) [48].

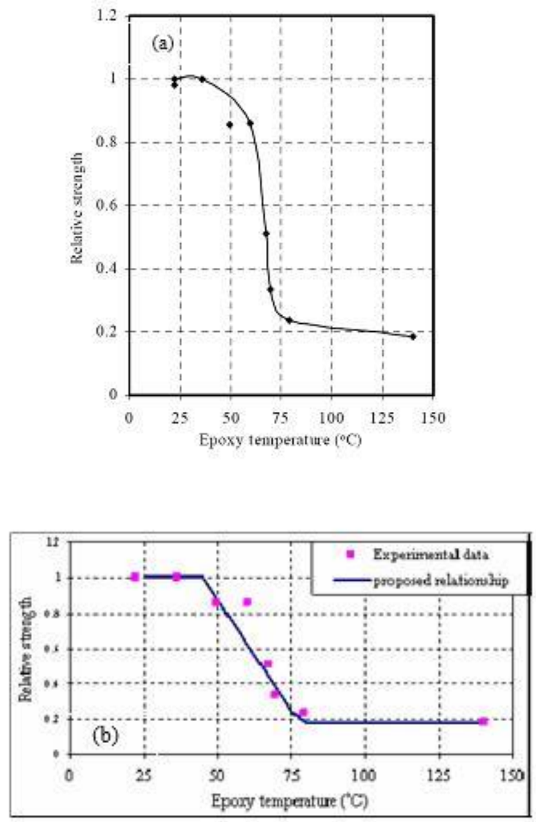


Figure 20. Relative bond strength variations with EBA temperature: (a) experimental data, (b) proposed relationship [48]

3.3.2 NSM FRP strengthening system

A study was conducted to explore the bond between CFRP textile and concrete using modified CBA at high temperatures. The reported bond-loss temperatures for loaded CFRP/concrete samples was found to be varied depending on the bonding length of CFRP textile. Samples with 50mm bonded length, the range was 235-245°C while it was 245-255°C for other tested specimens with 100mm bonding length [44]. Other group of researchers conducted experimental investigations [50,51] on concrete that damaged by high temperatures and then strengthened with CFRP laminate using NSM technique and two types of bonding adhesives. The high temperatures were 200,400, and 600°C for different exposure periods (1 and 2 hrs) and then CFRP was applied. The bonding agent was commercially EBA. CBA was used as bonding agent in other group of samples. The conducted results from testing samples that exposed to 200°C and using EBA showed that the residual bond strength was 94% and 86% for exposure periods of 1 and 2 hrs respectively. As the exposure temperature was increase to 400°C, less residual bond strengths (79% for 1 hrs and 75% for 2 hrs) were recorded. More reduction in the residual bond strength (49% for 1 hr and 41% for 2hrs) was achieved as the exposure temperature was increase to 600°C. However, less residual bond strengths was reported for fire-damaged samples that strengthened with CFRP using CBA for almost all exposure temperatures.

4. Conclusions & Recommendations

The current paper provides a review on some reported work by other researchers about bond efficiency of two types of FRP/concrete systems (ES and NSM) by means of adhesion and single-lap shear tests at ambient and temperature-based conditions. Two different bonding agents (EBA and CBA) were used to fabricate FRP/concrete systems to bond FRP sheets, textile or laminates. The following are drawn and proposed:

1. Most of the reported work for exposing FRP/concrete system to temperature-based conditions tests was carried out in laboratory with and without loading. Very limited work was reported to compare the findings from the experimental investigations with actual field data. Further work is required to perform bond evaluation on FRP/concrete system in both laboratory and site to provide more accurate evaluation of interfacial bond. Such data may assess in developing of new models to facilitate finding correlations between the experimental work and field data to achieve an accurate service life of concrete structures that strengthened with FRP using ES and NSM under severe conditions.
2. Variety of test arrangements are executed to evaluate the bond in FRP/concrete system at temperature-based conditions than ambient conditions. More details are considered during the exposure of loaded FRP/concrete samples to such conditions to provide, for example, protection to the free end (unbonded) FRP using insular/s
3. Modification of EBA affects the bond of FRP/concrete system that exposed to temperature-based conditions. Utilizing CBA has proven to be a good alternatives for EBA in improving the interfacial bond at temperature-based conditions since CBA provides both thermal and structural retrofitting properties for FRP/concrete system when exposed to such conditions. Developing bonding adhesives is required to overcome the limitations from using regular adhesives in FRP/concrete system to improve the bond efficiency under harsh conditions.
4. Reported failure modes are based on visual observations and most of these patterns were identified without giving attention to the primer/concrete interface. Utilizing techniques that based on image analyzing, for example, is proposed to characterize the failure surface

especially that contains combined failure patterns for ES FRP/concrete system that tested at various exposure temperatures.

5. Although ES is most popular FRP installation technique, NSM technique has more effective strengthening due to the larger bonded area with concrete compared to ES. Also, more protection is provided by NSM to FRP material when the strengthening system exposed to temperature-based conditions.
6. Limited work was carried out to investigate the bond integrity of ES FRP/concrete system using adhesion test at temperature-based conditions with and without loading. Further work is needed to contribute in understanding the bond behavior of this system under such conditions using various bonding agents.

Conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this manuscript.

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