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Bond strength of fly ash geopolymer with CFRP fabric after exposure to high temperature

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ABSTRACT: This paper presents a study on the bond strength of fly ash geopolymer as an alternative to epoxy bonding agent for carbon fibre reinforced polymer (CFRP) fabrics subjected to high temperature. CFRP fabrics of 300 mm bonded length were tested for bond strength by direct shear tests after three hours of exposure to elevated temperature at 100 ºC, 200 ºC and 400 ºC. It was found that the bond strength of fly ash geopolymer was less than that of the epoxy bonding agent at room temperature. However, the bond strength of epoxy was completely lost by the exposure to heat at 200 ºC, while the geopolymer retained its full bond strength up to the maximum testing temperature of 400 ºC. This shows the superior bonding performance of geopolymer with CFRP fabrics as compared to that of conventional epoxy bonding agent when exposed to high temperature.

1 INTRODUCTION

Concrete is the most used construction material because of its various advantages over other similar materials. With a huge amount of concrete being used in the construction industry, it is often found that structures or parts of structures either require upgrading due to old age, change of purpose of the structure or require repairing due to damage caused by inadequate design and construction, overloading or structural damage due to external factors. To add to this, the lack of regular maintenance, inspections and implementations of preventative measures can make the situation even worse, which results in a need for strengthening, retrofitting and sometimes the total demolition of the affected structures. When such situations arise, there is a choice of tearing down a structure and rebuilding or upgrading and repairing. If upgrade of a structure by the option of strengthening is chosen, it is common to utilize fibre reinforced polymers (FRP) in the form of reinforcing bars embedded into the concrete section, or as sheets, plates and fabrics placed around a concrete member in the form of externally bonded reinforcement (Maraveas et al. 2012). Strengthening of old concrete structures is gaining more attention since this option offers a more environmentally sustainable solution as compared to demolition and building of new structures.

When using FRP to strengthen and repair concrete structures, epoxy resin is used as the typical bonding agent to provide effective bonding of the sheets, plates or fabrics with concrete surface. The method of strengthening by FRP provides several advantages over the other rehabilitation methods, most noteworthy of which are simple in-situ installation, fast on-field construction and little disturbance to surroundings due to the rehabilitation work (Maraveas et al. 2012). However, there exists some concerns as well associated with the behaviour of FRP materials bonded using epoxy resins, especially at exposure to high temperature. Externally bonded FRP materials usually show severe degradation of strength and stiffness at elevated temperatures. This is because of the reduction in bond strength of the adhesive at temperatures above the glass transition of epoxy resins (Foster and Bisby, 2008). The loss of bond strength at elevated temperature results in reducing the ability of an adhesive to transfer the force between the FRP material and the concrete member.

Some of the other limitations of epoxy bonded FRP systems are that the epoxy fume is considered hazardous for the manual workers, epoxy based composites do not let any vapor through which can lead to a durability problem and the application of epoxy is not possible on a wet or moist surface nor is it possible if the temperatures are below 10°C (Wiberg, 2003).

Considering the limitations and issues with the current bonding agents mentioned above, development of a heat resistant adhesive would help ensure the strength of FRP strengthened structures in case of an accidental fire and for structures required to endure high temperature in their service life. It was shown that up to 65% bond efficiency of epoxy resins could be achieved by using polymer modified cementitious materials as bonding agents (Wiberg 2003). Geopolymer is an emerging binding material that is produced by the alkaline reaction of pozzolanic materials of geological origin such as metakaolin or industrial by-products such as ground granulated blast furnace slags (GGBFS) and fly ash. Due to their ceramic-like properties, geopolymers are believed to possess good fire resistance as well as good bonding properties (Kong and Sanjayan 2010, Sarker et al., 2007). Fly ash based geopolymers have shown superior residual strength and resistance to cracking and spalling at high temperature exposures when compared to ordinary Portland cement (OPC) based binders for concrete (Sarker and McBeath, 2015; Sarker and de Meillon 2007). Since fly ash geopolymer showed good bonding and heat resisting properties in concrete applications, its use as an alternative heat resisting bonding agent for FRP fabrics to OPC concrete surface has been studied in this paper.

2 EXPERIMENTAL WORK

2.1 Materials

2.1.1 Geopolymer

A low-calcium Class F fly ash was used as the aluminosilicate source for production of the geopolymer binder. The chemical compositions of the fly ash are given in Table 1. The alkaline liquid used for reaction with the fly ash consisted of a mixture of sodium hydroxide (NaOH) solution of 10M concentration and commercial sodium silicate (Na_2SiO_3) solution. The alkaline liquid to fly ash mass ratio was 0.35 and the sodium silicate to sodium hydroxide mass ratio was 2.5. The sodium hydroxide solution was prepared by dissolving NaOH pellets in potable water. The sodium silicate consisted of 14.7% Na_2O, 29.4% SiO_2 and 55.9% water. The cube 28-day compressive strength of the hardened geopolymer paste was determined as 62 MPa.

Table 1. Chemical composition of fly ash

Element	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	TiO_2	LOI
Mass (%)	52.5	26.3	3.56	10.1	0.76	1.71	0.11	0.41	0.75	1.49	1.05

2.1.2 Carbon fibre fabric

The carbon fiber fabric used for the bond tests was a 230 g/m^2 woven unidirectional carbon fiber fabric, designed for structural strengthening applications. It was supplied in a 10 meter roll which was 500 mm wide. For the experiments, 50mm strips were precisely cut which contained 16 woven strands. The fabric thickness was 0.131 mm. The tensile strength and elastic modulus were 4.3 GPa and 238 Gpa, respectively. The physical and mechanical properties of the carbon fiber fabric are given in Table 2.

2.1.3 Epoxy resin

A commercial epoxy resin was used as the control adhesive for the comparative bond strength tests. It is a 2-part epoxy impregnation adhesive, which is designed to be used with carbon fiber fabric reinforcement for application to concrete surfaces. The resin paste and the hardener paste are mixed at the ratio of 4:1 giving a density of 1.31 kg/Litre. The tensile strength and E-modulus of the hardened epoxy resin are 30 MPa and 4.5 Gpa, respectively. The service temperature of the adhesive is -40°C to +50°C.

2.1.4 Concrete

Rectangular concrete blocks of 100mm x 100mm x 300mm were cast for pull off tests of the carbon fabrics. The concrete mixture consisted of 375 kg/m^3 of OPC with water to cement ratio of 0.4, 1220 kg/m^3 of coarse aggregates and 676 kg/m^3 of fine aggregates. The 28-day compressive strength of the concrete was determined as 52 MPa.

2.2 Test specimens and procedure

The specimens for the bond consisted of a length of carbon fibre fabric bonded to a concrete block as shown in Figure 1. A total of 24 concrete blocks were cast and cured in water for 28 days. Prior to bonding the carbon fibre fabric, the surface of the concrete block was sandblasted to remove cement laitance, loose and friable material and to achieve a profiled open textured surface.

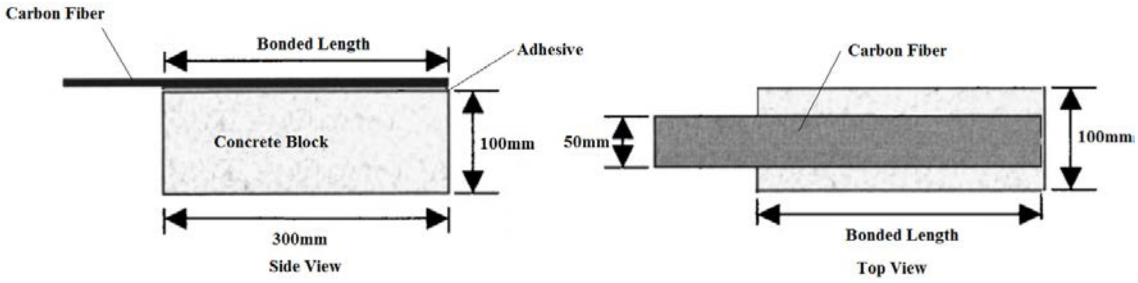

Figure 1. Specimens for bond test of CFRP fabric to concrete.

Once the surface was prepared, one set of control specimens was produced by bonding the carbon fibre with a two-part epoxy resin as per the manufacturer's instructions. Another set of specimens was prepared by bonding the fabric with fly ash geopolymer paste. The geopolymer paste was mixed in 4L batches, and was applied to the concrete blocks in two layers, as shown in Figure 2. A 2mm layer of geopolymer paste was applied below the carbon fibre fabric and another 2mm layer on top of the fabric. This method was consistent with the usual procedure of bonding FRP fabrics to concrete surface (Wieberg, 2003). The bonded length of the CFRP fabric was 300 mm for all the specimens. The carbon fibre fabric on the pulling end of the block was placed into a protective plastic sleeve to ensure that fibres were not damaged. To ensure hardening of epoxy and geopolymer paste, the specimens were cured for 28 days in ambient temperature before exposure to elevated temperature.

Figure 2. Bonding of CFRP fabric by geopolymer paste.

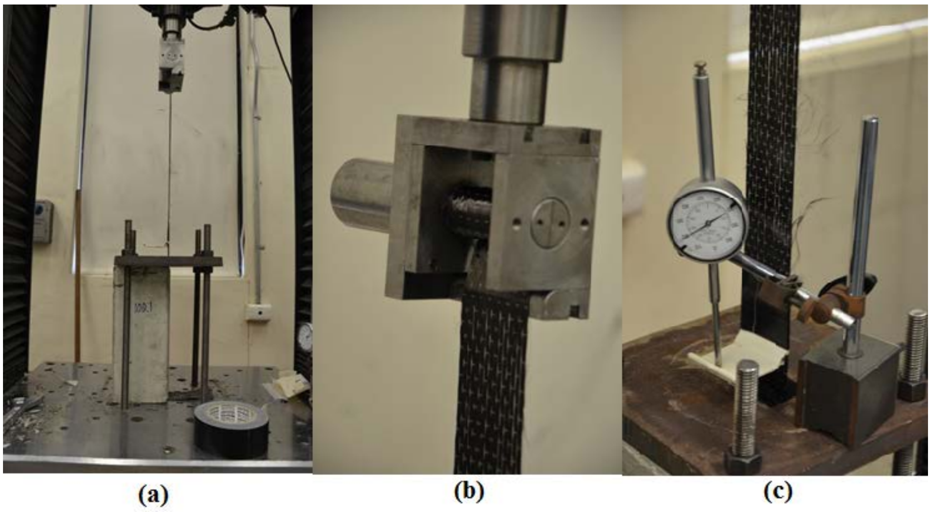

Figure 3. (a) Alignment and positioning of specimen, (b) Securing carbon fiber fabric to the grip for pull off, (c) Measurement of slip by dial gauge.

Thermal exposure of the specimens was accomplished by placing the specimen in a programmable electric furnace designed for a maximum temperature of 1200 °C. The variable temperatures that were tested were ambient, 100 °C, 200 °C and 400 °C. The specimens were placed into the furnace at room temperature, the target temperature was reached at increments of 4.4 °C/minute. Once the target temperature was reached it was sustained for 3 hours, the specimens were then allowed to cool in the furnace slowly to room temperature. This temperature was chosen to replicate temperatures that may be experienced by insulated FRP systems during actual fire situations (Foster and Bisby, 2008).

To perform the bond test, a steel frame was fabricated to secure the concrete block in place as shown in Figure 3(a). A grip for the fabric as shown in Figure 3(b) was manufactured to pull the fabric off the concrete block resulting in a direct shear to the bonding agent. This set-up was used to apply tension to the fibre fabric in its centre axis. The test specimens were carefully set up in the testing machine, making sure that the carbon fibre fabric was completely aligned with the centre axis of the machine so that no force was applied in the normal direction that may cause peeling of the fabric. The pull-out end of the carbon fibre fabric was then attached to the pulling head of the testing machine as shown in Figure 3(b). Once some tension was applied to the fabric, a dial gauge was placed at 30 mm above the surface of the concrete block to measure the slip, as shown in Figure 3(c). The dial gauge was recorded by a video camera so that bond slip data could be retrieved. Once the specimen was secured in the machine and accurately aligned, load was applied to the specimen under a displacement control mode at a rate of 5 mm per minute until failure. The load and displacement data were recorded with an electronic data logger and the specimens were visually inspected during and after the test. The bond strength was determined by dividing the maximum value of the pull-out load by the bonded area of the CFRP fabric. Three specimens were tested for each case and the average value of the bond strength is reported.

3 RESULTS AND DISCUSSION

3.1 Observation of the specimens before the bond test

Upon initial observation of the epoxy bonded specimens during and after exposure to elevated temperature, the specimens that were exposed to 100 °C showed no change in physical appearance. After 3 hours of exposure to the heat, some minor surface burns were observed at the corners of the specimens. The colour of the adhesive changed from transparent to a light grey, however there were no obvious signs of deformation or weakening along the bonded surface.

Figure 4. Delamination of epoxy bonded CFRP fabric by heat.

The specimens that were exposed to higher temperatures such as 200 °C and 400 °C however, showed severe signs of melting epoxy, there was a strong odour of melting solvents with melted epoxy evident on the side of the concrete specimens. Upon touching of edges, the epoxy was very soft and weak. After exposure of the specimens to 200 °C and 400 °C, when they cooled down to room temperature, the epoxy was not as soft and malleable as in the high temperatures but was still relatively soft compared to the samples that were not exposed to heat. It was also evident that upon cooling, the laminate layer of carbon fibre and epoxy had warped and completely delaminated off the concrete surface as shown in Figure 4.

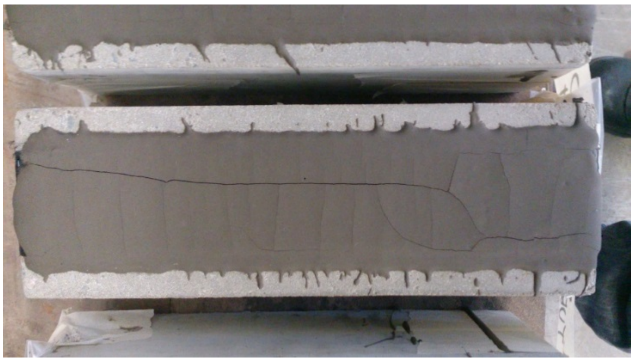

Figure 5. CFRP bonded to concrete by geopolymer paste.

Geopolymer paste was found to crack on the surface before exposure to heat, as shown in Figure 5. The cracking was primarily concentrated along the edges of the carbon fibre fabric and directly above the fabric, the surfaces in contact with concrete did not show any cracking. The companion cube specimens did not show any sign of such cracking. A possible explanation for this is, due to the paste not being able to penetrate the carbon fibre fabric, it was unable to penetrate to the lower layer of geopolymer paste. With this, there is only a thin layer of paste formed above the fabric, which is not bonded firmly to the fabric and the lower layer of geopolymer paste. Thus, the top layer of geopolymer pasted showed formation of cracks because of shrinkage.

No changes could be seen in the physical appearance of the geopolymer bonded specimens during or after exposure to elevated temperature up to 400 ºC. There was no additional cracking or brittleness or softening of the geopolymer binder by exposure to heat. This observation is consistent with the previous studies that showed the excellent heat resisting properties fly ash geopolymer concrete and mortars.

3.2 Bond strengths of epoxy bonding agent and geopolymer paste

The bond strength of each specimen was calculated from the maximum value of the pull-out load of the specimen. The mean values of the bond strengths are presented in Figure 6. By analysing the bond strength results shown in Figure 6, it can be seen that at ambient temperature, the bond strengths of the epoxy adhesive and geopolymer paste were 0.56 MPa and 0.32 MPa, respectively. Thus, the epoxy adhesive have a much higher bond strength than the geopolymer paste before exposure to heat. This bond strength of the epoxy resin however, is heavily dependent on the surface tensile strength of the concrete more so than the strength of the adhesive. This is because the epoxy bonded specimens failed due to cracking of the concrete substrate. On the other hand, the geopolymer bonded specimens failed by delamination of the CFRP fabric from the concrete surface without any concrete substrate sticking to the fabric.

Once the specimens were exposed to heat, it can be seen that the epoxy resin lost more than half of its bond strength at 100 °C, and in this case it is the failure of adhesive that occurred rather than failure of the concrete surface. On the contrary, it can also be seen that as the geopolymer bonded specimens were exposed to elevated temperatures the bond strength was not affected throughout the temperature range up to 400 °C.

Once the exposure temperatures were raised to 200 °C and 400 °C the epoxy bonded specimens were no longer suitable for bond test as the contact between the CFRP fabric and concrete was mostly lost due to warping and delamination by the heat. Thus, these specimens had no further residual bond strength remaining. It can also be noted that the specimens with geopolymer paste adhesives failed at the same location at all temperatures, which was at the interface between the geopolymer paste and the carbon fibre fabric, therefore the surface tensile strength of the concrete was not influential on these results.

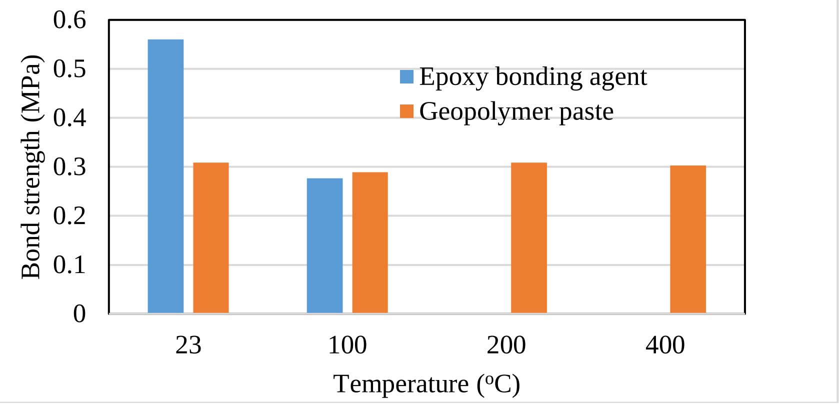

Figure 6. Bond strength of epoxy bonding agent and geopolymer paste.

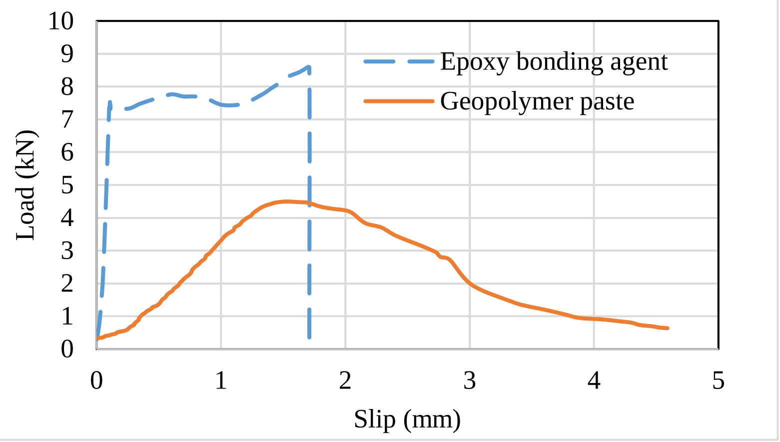

Figure 7. Load-slip curves of epoxy bonding agent and geopolymer paste.

3.3 Load-slip behaviours of the epoxy and geopolymer bonded CFRP fabrics

The typical pull-out load versus slip of the CFRP fabric bonded with epoxy resin and geopolymer paste are shown in Figure 7. It can be seen that there was much less bond slip in the specimens bonded by epoxy as compared to those bonded by geopolymer. For the specimen bonded by epoxy, there was a steep linear increase in load within which there is virtually no slip. Once near to maximum load was reached and the concrete surface started to fail by disintegration of the substrates, the maximum load was sustained for about 1.5 mm of slip until sudden failure and complete delamination of the fabric occurred.

In comparison, the specimens bonded with geopolymer paste, there was a gradual linear increase in load, in which there was about 1.7 mm of slip. Once the maximum load was reached, the load did not sustain for long and followed a gradual reduction thereafter. The load continued to reduce until the entire bonded length of the fabric had slipped and minimal load was supported only by friction between the geopolymer paste and the fabric. Even at near the zero load, there was no full loss of contact between the fabric and the concrete surface. By observation slip in the specimens bonded by geopolymer paste occurred gradually and had a ductile failure behaviour.

Overall it is clearly shown that the bond formed by geopolymer paste is less effective when compared to the bond formed with an epoxy resin at ambient temperature. At elevated temperatures, however, the performance of geopolymer paste is far superior to that of epoxy resin. The bond failure behaviour, as indicated by load-slip curves of these bonding agents, are also different.

4 CONCLUSIONS

A commercial epoxy resin and fly ash geopolymer paste were used as bonding agents to bond CFRP fabric to concrete surface. Bond tests were performed to investigate the bond strengths and failure behaviours of the specimens after exposure to high temperature. The following conclusions are drawn from the study:

- Geopolymer bonded specimens achieved approximately 50% of the bond strength of the specimens bonded by epoxy resin at ambient temperatures. This is because the geopolymer paste did not wet through the CFRP fabric and showed shrinkage cracks.
- Elevated temperatures up to 400 °C did not reduce the bond strength of geopolymer whereas temperatures above 100 °C severely reduced the bond strength of epoxy resin. Heating at 200 °C and 400 ºC caused complete loss of bond strength and delamination of the epoxy bonded CFRP fabric.
- Failure of the epoxy bonded specimens occurred suddenly by tensile disintegration of concrete substrates sticking with the CFRP fabric. In contrast, failure of the geopolymer bonded specimens occurred due to the gradual slip of the CFRP fabric against the concrete surface.

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