

Strength of concrete with FRP fabric confinement using geopolymer bonding agent after exposure to high temperature

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ABSTRACT: Epoxy based bonding agents have been commercially developed for effective bonding of FRP with concrete for strengthening purposes. However, epoxy resins usually show loss of strength and stiffness at high temperature. This paper presents a study on the comparison of strengths of concrete cylinders confined by basalt fibre reinforced polymer (BFRP) fabrics bonded by an epoxy based agent and fly ash geopolymer. Concrete cylinders were wrapped by two layers of basalt fabric and tested for compressive strength after exposures to temperatures of 65 °C to 350 °C. The mean unconfined compressive strength of concrete cylinders was 40 MPa and the confined compressive strengths increased by 25% and 17% for using epoxy and geopolymer bonding, respectively. Both the bonding agents retained the enhanced strengths after heating the specimens at 65 °C for 90 minutes. After exposure to 150 °C, strength enhancement of the specimens using epoxy bonding decreased to 10% with slight further decreases for the increase of temperature up to 350 °C. On the other hand, the strength enhancement remained almost same for using geopolymer bonding agent for up to 350 °C exposure. Failure occurred by tearing of the fabric in both cases. The reduction of strength enhancement in the epoxy bonded specimens is attributed to the thermo-oxidative degradation of the epoxy resin.

1 INTRODUCTION

The global increase in the maintenance of infrastructures has sparked a demand for cheaper, easier and effective solutions to rehabilitate deteriorating structures or enhance concrete structures. Usually there are issues that need to be overcome when strengthening structures, especially when rehabilitating structures that are exposed to corrosive environments or potential elevated temperatures. Fibre-reinforced polymers (FRP) have been used as a common material for strengthening of structures. FRP woven fabrics usually possess the desirable properties for strengthening such as a high strength to mass ratio, ease of application to existing structures and high resistance to corrosion. These materials, when externally bonded to concrete structures using certain resins, have proven to greatly enhance the shear, flexural and axial strengths of concrete structures. In applications where corrosion is a significant concern such as in offshore structures, FRP reinforcement is shown to be superior as compared to typical steel plate reinforcing methods whereby the steel loses its structural integrity due to corrosion. There is a variety of different FRP materials such as glass fibre reinforced polymer (GFRP), carbon fibre reinforced polymer (CFRP) and basalt fibre reinforced polymer (BFRP) that can be used to enhance strength of existing structures. Each type of FRP has distinct properties that make them suitable for the given application.



Wrapping methods are crucial in the reinforcement of concrete as they have a direct correlation to the enhancement of strength. Wrapping is shown to be advantageous over the method of steel plate reinforcement, as FRP can be easily crafted into the desired shape and installed on site. There are different ways in which the FRP can be externally wrapped around concrete, with strengthening different mechanical properties in different proportions (Sen et al, 2012). It has been found that some wrapping techniques are more appropriate when reinforcing for specific properties. For instance, strip wrapping is found to enhance the shear strength of concrete beams more than that for full wrapping (Yoganathan and Mahendran, 2015). However, full wrapping is usually more effective to enhance the axial load capacity of columns.

De-bonding of FRP from the concrete surface is a common type of failure. In addition to the external load, this can also occur due to the environmental factors such as high temperature that affects the adhesive bonding of an FRP to the concrete surface. These factors can be mitigated through selection of an adhesive that attains strong structural and chemical properties. Commercial epoxy resins are currently the most commonly used bonding agents for FRP reinforcement. However, the thermal properties of epoxy resins are a major drawback, specifically past the glass transition temperature. After this temperature, the epoxy begins to transition into a rubbery state down at the molecular level. The typical glass transition temperature of commercially available epoxies ranges from 60 °C to 82 °C (American concrete Institute, 2017). If the elevated temperature lasts for an extended duration, the transition becomes irreversible, whereby the adhesion strength and mechanical properties of the epoxy are significantly reduced (Urbaniak, 2018). This is a significant limitation of epoxy resins for applications in structures with potential exposure to high temperature such as an event of accidental fire, in which case the bond between FRP and concrete surface would fail to make the FRP strengthening ineffective. Therefore, new bonding agents with high resistance to elevated temperatures are to be explored.

Geopolymers are inorganic aluminosilicate materials that possess relatively strong mechanical properties as well as desirable thermal properties, the use of which can be explored as an alternative bonding agent for FRP. Geopolymers are produced by reaction of a material that is rich in aluminosilicate, such as fly ash with an alkali such as sodium hydroxide. Due to their ceramic-like properties, geopolymers show good fire resistance as well as good bonding properties (Kong and Sanjayan 2010, Sarker et al, 2007). Fly ash based geopolymers have shown good residual strength and resistance to cracking and spalling of concrete at high temperature exposures when compared to Portland cement based binders (Sarker and McBeath, 2015; Sarker and de Meillon 2007). Blending of low calcium fly ash with ground granulated blast furnace slag (GGBFS) has been found to be an effective way to control setting and hardening of geopolymers at room temperature making it possible to use without the need for heat curing (Deb et al, 2013; Nath and Sarker, 2017). It was also shown that fly ash geopolymers retained the bond strength of externally bonded CFRP fabric with concrete surface at a high temperature of 400 °C (Sarker et al, 2017). Therefore, this study investigated the axial strength enhancement of concrete confined by FRP fabric using geopolymer as the bonding agent at high temperatures.

2 EXPERIMENTAL WORK

2.1 Materials

2.1.1 Geopolymer

A locally available class F fly ash and a combination of 10M sodium hydroxide (NaOH) solution with commercial sodium silicate (Na_2SiO_3) solution was used as for production of geopolymer paste. The chemical compositions of fly ash are given in Table 1. The mass ratios of total alkaline

liquid to fly ash was 0.45 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 contained 14.7% Na₂O, 29.4% SiO₂ and 55.9% water. The freshly mixed geopolymer paste is shown in Fig. 1.

Table 1. Chemical composition of fly ash

| Element | SiO ₂ | Al ₂ O ₃ | CaO | Fe ₂ O ₃ | K ₂ O | MgO | MnO | Na ₂ O | P ₂ O ₅ | TiO ₂ |
|----------|------------------|--------------------------------|------|--------------------------------|------------------|------|------|-------------------|-------------------------------|------------------|
| Mass (%) | 52.5 | 26.3 | 3.56 | 10.1 | 0.76 | 1.71 | 0.11 | 0.41 | 0.75 | 1.49 |

2.1.2 Basalt fibre reinforced polymer (BFRP) fabric

The FRP fabric used for confinement of the concrete cylinders was a 300 g/m² twill weave basalt fiber fabric, designed for structural strengthening applications. It was supplied in a 10 meter roll which was 1 m wide. For wrapping of the concrete cylinders, 200 mm wide strips were cut and used. The tensile strength of basalt fibers vary between 1000 MPa and 1600 MPa. The material has a high UV protection property and remains stable at up to 1000 °C. The BFRP used in this study is shown in Fig. 1.

2.1.3 Epoxy resin

A commercial epoxy resin known as Sikadour was used as the control adhesive for comparison with geopolymer bonding. It was a 2-part epoxy impregnation adhesive, designed for bonding of FRP fabrics to concrete surface. 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

Concrete cylinders of 100 mm diameter and 200 mm height were cast for compressive strength tests with and without wrapping by BFRP. The concrete mixture consisted of 360 kg/m³ of OPC with water to cement ratio of 0.40, 1220 kg/m³ of coarse aggregates and 676 kg/m³ of sand. The mean 28-day compressive strength of the concrete was determined as 40 MPa.

2.2 Test specimens and procedure

The test specimens were 100 mm diameter × 200 mm height concrete cylinders. The concrete specimens were cured in water for 28 days and then the surface was sandblasted to remove cement laitance, loose and friable material and to achieve a profiled open textured surface.



Figure 1. Geopolymer paste (left) and BFRP fabric (right).

Once the surface was prepared, one set of specimens were wrapped with BFRP by using a two-part epoxy resin as the bonding agent. Another set of specimens were prepared by bonding the fabric with fly ash geopolymer paste. The geopolymer paste was mixed in 4L batches, and was applied to the concrete cylinders in two layers, as shown in Figure 2. A layer of geopolymer paste was first applied on the fabric and the cylinder was rolled on it to get the fabric wrapped around the cylinder. Another layer of geopolymer paste was then applied on the surface of the fabric and rolled by a roller. The BFRP fabric was used in two layers with an overlap of 50 mm at the end. A similar approach was used to prepare the epoxy bonded BFRP confined cylinder specimens.



Figure 2. Wrapping of BFRP fabric to concrete cylinders by geopolymer paste.



Figure 3. Heating of the specimens in a furnace (left) and compression test after cooling (right)

A set of BFRP specimens were kept at room temperature and the other specimens were exposed to high temperature in an electric furnace after 14 days of curing at 20 °C. The specimens were exposed to maximum temperatures of 65 °C, 150 °C, 250 °C and 350 °C. The target maximum temperature was reached by increasing the temperature at a rate of 5 °C/minute. Once the target temperature was reached it was maintained for 1.5 hours. The specimens were then allowed to cool in the furnace slowly to room temperature by keeping the door open. The specimens were then tested for compressive strength. The heating and compressive strength test of the specimens are shown in Fig. 3. The average compressive strengths were determined from the results of three identical specimens for each case.

3 RESULTS AND DISCUSSION

3.1 Physical change in BFRP wrapped specimens by exposure to elevated temperature

Prior to heating of the epoxy was very stiff with no visible cracks or deformations during the 14 days curing period. For the specimens that were heated up to 150°C, there were no visual changes that could be identified. For the specimens that were heated to 250°C, slight burns were present whereby brown spots could be seen with a slightly strong odour emanating from the ovens in which they were heated in. However, the specimens that were heated to 350°C had shown signs of physical change. During the heating of these specimens in the kiln, a strong white smoke was released for the full duration of the heating. It is to be noted that the smoke had been released purely from the epoxy burning and not from the fabric. After heating the specimens, and testing them during the following week, these specimens had still had a strong odour emanating from them. After heating all the specimens, the epoxy resin remained intact and secured to the fabric and concrete relatively well, as no delamination was visible. Although the epoxy had burnt quite severely in the 350°C specimens, the charring did not cause the epoxy to crack and fall off.

In the geopolymer bonded specimens, minor hairline cracks appeared on the surface at 14 days after wrapping. After heating the specimens, increased number of cracks were visible on the surface. However, the cracks were not deep enough to cause flaking. Instead, the cylinders remained rigid and intact. The cracking is attributed to shrinkage and dehydration caused by heating (Saha et al., 2019). No odour was released from the test specimens during heating. An orange tinge was observed on some specimens which is attributed to the iron oxide formed by fly ash at high temperature.

3.2 Failure of BFRP confined cylinders under compression

The typical failure patterns of the epoxy and geopolymer bonded BFRP confined cylinders under compression after high temperature exposure are shown in Fig. 4. The most common type of failure that occurred across all temperature ranges for the epoxy bonded specimens was vertical tearing of the fabric. This was followed by delamination of the fabric from the concrete, which caused the concrete to suddenly fail under the load. The tears often occurred in a singular straight line. However, in some cases, multiple jagged vertical tears were present. The fabric was stretched by the lateral expansion of concrete with the increase of compressive load. Eventually, when the fabric failed by tensile stress, concrete failed by cracking with the loss of confinement.

As shown in Fig. 4, the geopolymer bonded specimens mostly exhibited the same type of failure, where tearing of the fabric was followed by cracking of concrete. Due to the brittle nature of hardened geopolymer, flakes of geopolymer were spalled off at the locations where the fabric had torn and stretched. Spalling of geopolymer flakes also occurred from the surface since geopolymer paste did not penetrate through the fabric like the epoxy bonding agent.



Figure 4. Failure of BFRP confined specimens bonded by epoxy (left) and geopolymer (right).

3.3 Compressive strengths of BFRP confined cylinders bonded by epoxy and geopolymer

The mean unconfined compressive strength of concrete was 40 MPa. The percentage increase of compressive strength by two layers of BFRP fabric after exposure to different temperatures are plotted in Fig. 5. It can be seen that increases of compressive strength at 25 °C were 25% and 17% for epoxy bonding and geopolymer bonding, respectively. The enhancements of compressive strength remained same for both types of bonding agents after heating at 65 °C. Thus the epoxy provided a stronger bonding of the BFRP than geopolymer at normal temperature.

After exposure to 150 °C, the strength enhancement reduced to 10% for the epoxy bonded confined concrete. With further increase of temperature to 250 °C and 350 °C, the strength enhancements of the epoxy bonded specimens decreased to 9% and 8%, respectively. This

reduction in the confined compressive strength enhancement is attributed to the thermo-oxidative degradation of epoxy polymer beyond 150 °C and conversion of the some part of epoxy to gaseous products at higher temperatures. Such degradation of commercial epoxies after high temperature exposures were also reported in literature (Oussama et al 2012; Neiman et al, 1962). The thermal degradation of the epoxy polymer affected the bonding between BFRP fabric and the concrete.

On the other hand, the strength enhancements of BFRP confined concrete using geopolimer bonding remained almost the same after exposures to 150 °C, 250 °C and 350 °C. Therefore, there was no significant effect of high temperature exposure on the BFRP confined compressive strength of concrete using geopolimer bonding agent.

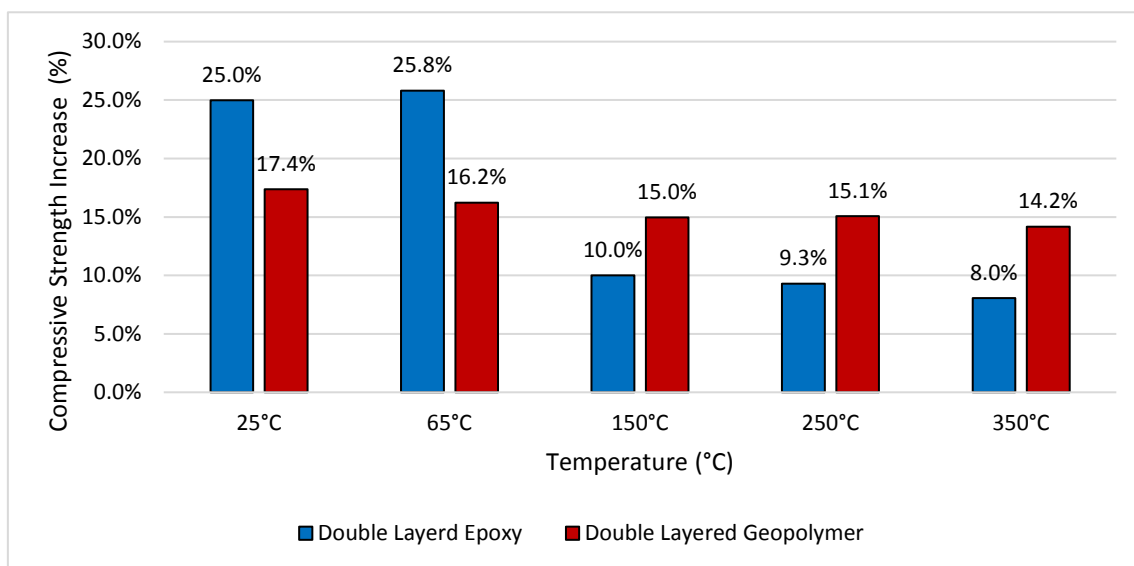


Figure 5. Strength increase of BFRP wrapped cylinders after high temperature exposure.

4 CONCLUSIONS

Concrete cylinders of 40 MPa unconfined compressive strength were wrapped by two layers of BFRP and tested for compressive strength after exposures to temperatures of 65 °C to 350 °C. The following conclusions are drawn from the study:

- The failure was characterised by tearing of the confining BFRP following by cracking of concrete in all cases.
- The confined compressive strength increased by 25% and 17% for using epoxy and geopolymer bonding, respectively. Both the bonding agents retained the enhanced strengths after heating the specimens at 65 °C for 90 minutes.
- After exposure to 150 °C, strength enhancement of the specimens using epoxy bonding decreased to 10% with slight further decrease for temperatures up to 350 °C. On the other hand, the strength enhancement remained almost same up to 350 °C for using geopolymer bonding agent.
- Despite some shrinkage cracks on the surface of geopolymer bonded specimens, geopolymer bonding retained the enhanced strength up to 350 °C, while the epoxy bonded specimens showed reduction of the strength after exposure beyond 150 °C. The reduction

of strength enhancement in the epoxy bonded specimens is attributed to the thermo-oxidative degradation of the epoxy resin.

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