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Potential Use of Ultra High-Performance Fibre-Reinforced Concrete as a Repair Material for Fire-Damaged Concrete in Terms of Bond Strength

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Abstract: The strength of concrete structures deteriorates after exposure to fire. Strength loss varies with elevated temperature, fire duration, and the mechanical properties of concrete. Repairing and strengthening affected structures are important to improve their performances. Fire-damaged concrete has been repaired using fiber-reinforcing polymer. The superior properties of ultrahigh performance fiber-reinforced concrete (UHPFRC) make it suitable as a repair material. Furthermore, an excellent repair material should be able to bond properly with the substrate and maintain its structural integrity. The aim of this paper is to review the potential use of UHPFRRC as a repair material for fire-damaged concrete in terms of bond strength. Previous studies showed that developing efficient rehabilitation techniques that enable fire-damaged structures to be restored has some challenges. Whether UHPFRC can be used as a repair material particularly for fire-damaged concrete structure is recommended to be proven in future studies.

Keywords: UHPFRC, bond strength, repair material, fire damaged, concrete

1. Introduction

Fire is one of the most severe hazards that may happen to build structures (Garlocka et al. 2012). Excellent and proven fire resistance of concrete offers protection of life, property, and environment in case of fire. The slow rate of heat transfer makes concrete an effective fire shield not only between adjacent spaces but also to protect itself (Kodur 2014). Concrete undergoes different types of fire damage depending on the temperature it is exposed to. After being exposed to high temperature, concrete experiences cracking, color change, as well as a reduction in modulus elasticity, compressive strength, and spalling. Fire-damaged reinforced concrete (RC) structures can generally be rehabilitated by applying proper retrofitting methods. Strengthening, maintenance, and repair of concrete are measures that are becoming increasingly popular in the field of civil engineering. Furthermore, many repair materials can be developed. To become an excellent repair material, a material should be able to bond properly with the old concrete and maintain its structural integrity (Banthia et al. 2014). Tayeh et al. (2013) showed that ultrahigh performance fiber-RC (UHPFRC) is a suitable

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repair material. Its superior properties in terms of durability and strength make it suitable in rehabilitation work. The bond strength between UHPFRC and a concrete substrate has also been shown to be strong enough. Based on these findings, this paper reviews fire-damaged concrete, repairing work, and materials that can be used to repair fire-damaged concrete, as well as its properties.

2. Fire-Damaged Concrete

The properties of concrete deteriorate when it is subjected to high temperature. This is due to the changes of physical properties and chemical composition of concrete. According to Mazza et al. (2015) and Ma Q et al. (2015), the compressive strength of concrete exposed to high temperature occurs in three stages which at room temperature up to 300°C, the compressive strength keeps constant. Then at 300-800°C, the compressive strength of concrete drop drastically and at more than 800°C temperature, concrete lost its compressive strength. Moreover, previous studies reported that, concrete exposed to high temperature experiences major changes in its components. These changes occur as the temperature increases. At about 100 °C, the temperature of concrete remains constant for a short period of time (Zuki et al, (2015a, 2015b)). This phenomenon occurred due to the evaporation of free water within concrete. Afterward, at approximately 400 °C, capillary water within the concrete is lost utterly. At this temperature, C-S-H gel dehydrates; calcium hydroxide and calcium aluminates decomposition (Schneider, 1988). Along with the increase in temperature, changes in the aggregate take place. Aggregates start to transform from α-phase to β-phase at approximately 573 °C. Fig. 1 shows the relationship between moisture content and possibility and extent of spalling. This phenomenon causes the concrete to expand, thereby breaking down the concrete (Shneider, 1988; Khoury et al. 2002). Calcareous aggregates, such as limestone, start to disintegrate when the temperature reaches 600 °C and above. Above this temperature, the strength of concrete is substantially reduced and crumble under slight pressure (Shneider, 1988; Khoury et al. 2002).

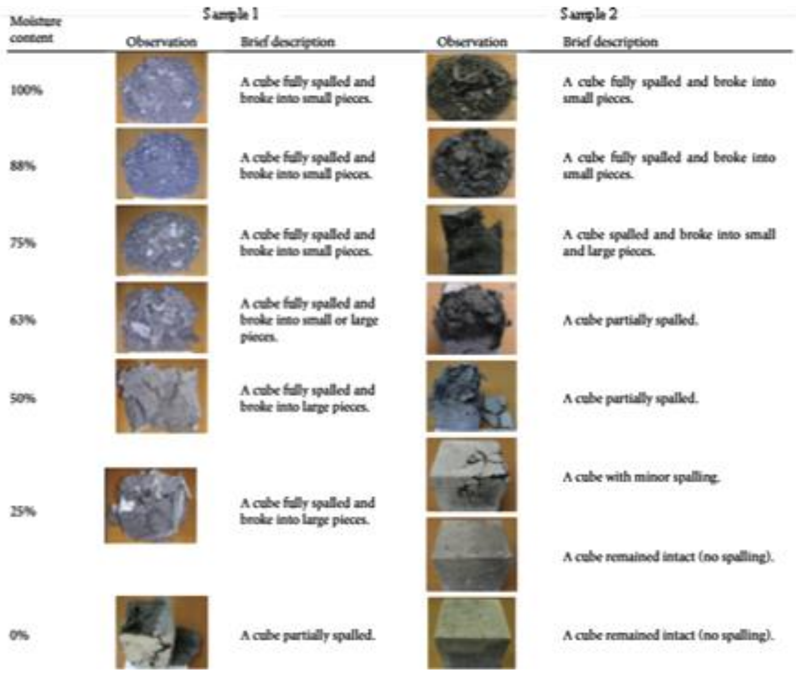

Fig. 1 - Relationship between moisture content and possibility and extent of spalling (Ma Q et al.,2015)

According to Phaedonos et al. (2011), concrete loses up to 30%–40% in strength once the temperature reaches 300 °C. The residual flexural strength of concrete also decreases along with an increase in temperature. Li et al. (2004), observed a reduction in strength when concrete is exposed to high temperatures of up to 800 °C. The other author indicated that the flexural strength of concrete will gradually be lost at a temperature of 200 °C and above. As the temperature increases, the loss in strength decreases but at 1000 °C, the value becomes nullified Husem et al. (2006). High temperature has a negative effect on concrete strength (Dos Santos et al., 2016). At elevated temperature, the color of aggregates also changes. Most of these aggregates turn pink at approximately 250 °C to 300 °C with increasing temperature due to the oxidation of present Fe ions. Consequently, any pink/red discolored concrete should be regarded as being potentially weakened. The colour change of concrete is a vital indication of the effect of fire. Color changes also provide a good visual guide to estimate the temperature range at which concrete has been exposed to (Phaedonos et al. 2011). Concrete that has turned pink is damaged and should be replaced (Marxhausen et al. 2014). Spalling is the breaking off of the pieces of concrete from the surface and may occur when concrete structures are subjected to high temperature loading. According to Khaliq et al. (2017) spalling is a stochastic, abrupt, and nondeterministic process, and the occurrence of spalling is highly associated with high strength concrete (HSC). In addition, spalling will substantially reduce the mechanical properties of concrete structures and cause the thinning of the cross sections. This phenomenon leads to the reduction of fire resistance and in the worst case, the structure may even collapse. As mentioned before, HSC is more prone to spalling due to its dense microstructure than normal strength concrete (NSC). Therefore, the risk of spalling decreases with increasing porosity caused by the increasing amount of water, which evaporates during heating (Zhang et al. 2014). Cracking therefore provokes a speedy penetration of liquid, gaseous, and aggressive agents, which may weaken the durability and tightness of the structures (Rene et al. 1994; Ding et al. 2012). According to Hager, (2013), concrete heating will involve the process of removing water that is chemically bound with cement. The evaporation of water will have considerable effect on the mechanical strength of concrete. As stated by a previous research (Phaedonos et al. 2011), when temperature reaches 250 °C, free moisture in concrete is completely lost, and paste volume reduces. High temperature also changes concrete constituents. The free water in pores will evaporate at almost 200 °C. At almost 180 °C, the dehydration of chemically combined water in the cement gel will occur. Then, at a temperature of more than 500°C, the decomposition of the hydration product in concrete will occur (Park et al. 2015). As the temperature increases further, the decomposition of hydrates and the loss of chemically bonded water will take place (Zhao et al. 2014; Arioz et al. 2007). The result shows that high temperature has a significant influence on the properties and structure of concrete.

2.1 Effect of Heating Duration on Concrete Structure

The factors that affect the residual strength of concrete exposed to high temperature are heating rate, heating duration, stress or unstressed conditions of specimens, the type and size of aggregate, water/cement ratio, and the percentage of the cement paste. A previous study stated that longer heating duration leads to more concrete damage. Concrete structures that have been exposed to high temperature for 60 min experienced more damage than concrete that has been heated for 45 min. Zuki et al. (2017) observed similar findings in their research where the strength of columns exposed to high temperature for 90 min decreases significantly than columns with only 60 min of exposure time.

Experimental and theoretical analyses for columns heated at a constant temperature of 600 °C for different durations were compared (Bikhiet et al. 2014). The findings stated that when the period of heating increases from 10 min to 15 and 20 min, the strain of the columns increases by 45% and 55%, respectively. Both experimental and theoretical analyses showed that as the period of heating increases, the column stiffness decreases. The analysis also showed that with an increase in the period of heating of 10, 15, and 20 min, the corresponding column failure load decreased by nearly 12%, 15%, 25%, respectively, compared with C1 (unheated columns), as shown in Fig. 2. As shown in Fig. 2, C10, C12, and C13 indicate 10, 15, and 20 min of heating periods, respectively.

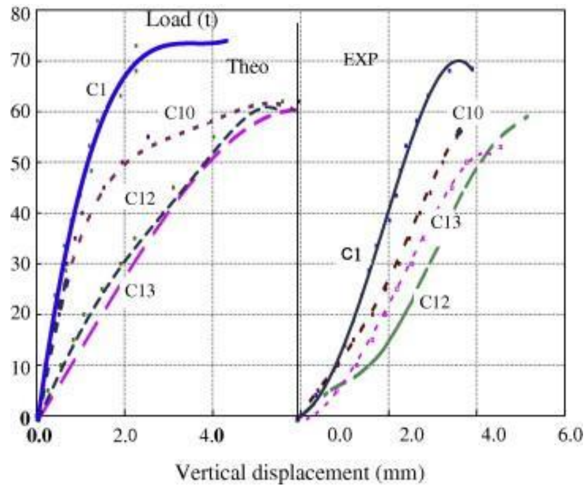

Fig. 2 - Experimental and theoretical load-vertical displacement relationship

2.2 Repair Work for Fire Damaged Structures

Options available in repairing fire-damaged concrete are limited. The common methods used are strengthening of structural members with fiber-reinforced polymer (FRP) and replacement with either shotcrete or in situ placement concrete (Khalid Heiza et al. 2014; Zaman et al. 2011). The main objective of every method is to enable the structural integrity of concrete structures to be restored and safely fulfill its intended function even after being exposed to high temperatures. In 1980s, retrofitting work for fire-damaged structures was done using normal concrete (NC). For instance, the fire-damaged St. Elizabeth Hospital was repaired with shotcrete and epoxy injection (De Lange et al. 1980). However, from time to time, retrofitting methods have been evolving. Thus, in April 2011, Dean’s Brook Viaduct in London was repaired using sprayed concrete reinforced with wire (Wheatley et al. 2014). Fig. 3 shows the before and after photos of the repair work.

Fig. 3 - Before and after photos of Dean's Brook Viaduct repair work

The latest innovation in terms of retrofit techniques is the use of FRP. Various research studies have been conducted to study the effect of FRP treatment on structure strength and overall structure recovery (Zuki et al. 2013; Chagas et al. 2016; Budhe et al. 2017; Shahidan et al. 2016). However, the effectiveness in terms of methods of wrapping and types of FRP used may differ depending on its application on different structural members (Masuelli, 2013).

Previously, Haddad et al. (2011) ferrocement, fibrous grout layers, and FRP sheets have been used as repair materials. These materials were used to repair heat-damaged shallow and T-shape beams. The presence of fiber in grout and polymer composites contributed to concrete flexural capacity and rigidity (Yaqub et al. 2011) when glass FRP is used to repair fire-damaged concrete columns. The results indicated an improvement in the mechanical properties of the repaired sample. Al-Rousan et al. (2015) concluded that thermal shock-damaged beams regain their original load-carrying capacity after being repaired using advanced composite materials. The composite materials used were carbon FRP plates and sheets. The load-carrying capacity and stiffness are recovered by approximately 99% and 90%, respectively.

Other methods in fire-damaged concrete rehabilitation work involve the removal of affected concrete part by using cleaning techniques such as sand, shot, and high-pressure water blasters. This step is crucial in removing thin layers of concrete surface. Usually, the removed part is replaced or overlaid with suitable repair material. A detailed repair process can be developed by referring to VicRoads Technical Note 72. The fire-damaged RC column regains its strength after being repaired with fresh concrete. The result showed that the repaired columns regain their original strength or achieve even higher strength than that of unheated columns after repair (Lin et al. 1996).

2.3 Ultrahigh Performance Fiber-RC (UHPERC) as a Repair Material

UHPFRC has a few main characteristics. It has more than 150 MPa compressive strength, 5 MPa tensile strength, and 4 MPa first cracking strength. In addition, it contains more than 2% of reinforcing fiber by volume and a tensile strength of more than 2000 N/mm² (Uchida et al. 2005). A previous research proved that UHPFRC can become a good repair material. The addition of fiber in concrete or mortar increases its strength, toughness, and impact resistance in various concrete applications (Nataraja et al. 2005). According to Tayeh et al. (2013b), UHPFRC shows excellent interlocking with the surface of substrates and results in high bonding strength. UHPFRC also has good rheological properties in its fresh state, thereby leading to easy casting using normal concreting equipment. It also has high resistance to overcome severe environmental conditions. Another previous study Baharuddin et al. (2005) stated that UHPFRC can potentially be used for the repair and reuse of fire-damaged concrete. In this study, a laboratory test has been conducted to determine the bond strength between fire-damaged NC substrate and UHPFRRC. The result revealed that the bond strength between the UHPFRC and fire-damaged substrate depends on the surface moisture condition of the substrate. In this test, highest bond strength is achieved for the saturated-surface-dry (SSD) surface. Li et al. (2017) investigated damaged columns that were repaired using HPFRCC containing fly ash. The effectiveness of the repairing schemes was evaluated by comparing load-carrying capacities, displacement ductility, stiffness, and energy dissipation of the columns. The results indicated that the load-carrying capacity and ductility of the repaired columns can become 14% and 29% higher than those of the original columns. With axial loads during the repair process, the repaired columns show better cyclic performance. Increasing the repair height beyond the plastic hinge zone slightly improves the load-carrying capacity and ductility. Considering the performance-to-cost ratio, the repair height of HPFRCC is recommended to be 1.5-fold higher than either La Morge River in Switzerland the depth or width of the damaged column. Flexural behavior of RC beams strengthened with UHPFRRC also shows promising results (Al-Osta et al. 2017). UHPFRC was first applied for the repair work of existing concrete structures in Europe during the European project called Sustainable and Advanced Materials for Road Infrastructures in 2004. A bridge over the La Morge River in Switzerland was widened and rehabilitated using UHPFRC of the CEMTEC multiscale® family. The bridge had no water-proofing membrane, and the edge beams were severely damaged by chloride ingress. The bridge was widened using a prefabricated UHPFRC edge beam and a reinforced beam. Then, the existing concrete overlay and edge beam were replaced by a UHPFRC overlay and edge beam, respectively, as shown in Fig. 3.

3. Bond Strength

Bond strength is the adhesion between repair material and old concrete and can be the weakest link of the system. Good bond strength is a key factor of a good repair system. Repair material and concrete must be able to act as one and perform monolithic action in effective ways (Silfwerbrand et al. 2011). Bond strength refers to the maximum force divided by the interface area under a condition where failure occurs completely at the interface (Bonaldo et al. 2005). If failure occurs on the substrate, then the bond strength is greater than the tensile strength of the substrate. Several tests can be performed to evaluate interface among concrete layers. These tests can be categorized into three different groups, which include axial, bending, and shear tests, as shown in Table 1.

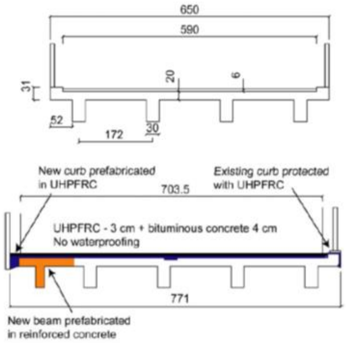

Fig. 4 - Cross-section of the bridge (a) before and (b) after rehabilitation (Brühwiler et al. 2005)

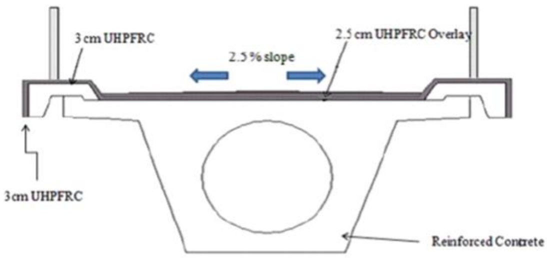

Fig. 5 - Cross-section of bridge rehabilitation with UHPFRC (Brühwiler et al. 2005)

Table 1. Evaluating concrete- to concrete bond strength

Group	Test	Standard
Axial	Pull-off	BS EN 1542 ASTM C1583 BS 1881: Part 207
	Direct Tension	ASTM C1404 CAN/CSA A23.2 6B
	Splitting	NP EN 12390-6 ASTM C496
Bending	Flexural Strength	NP EN 12390-5 ASTM C78
Shear	Direct Shear	-
	Bi-Surface	-
	Slant Shear	ASTM C882
	Push off	-

4. Substrate Preparation

Espeche and Leon (2011), portrayed that bond mechanisms between two cementitious materials are based on bond adhesive (microscale) and cohesion (macroscale). In practice, this concrete-to-concrete bond is known to be influenced by a variety of factors such as surface condition (roughness, cleanliness, presence of microcracks, and wetting condition), compaction method, strength and thickness of the overlay material, substrate strength, aggregate gradation, curing process, and age of the bond.

4.1 Substrate Surface Roughness

A good quality bond between NC substrate and repair material is important in ensuring repair efficiency. Roughening the substrate surface to boost its bonding strength with a new layer of concrete is common. However, if done incorrectly, then it will lead to microcracking, which interferes with concrete quality and strength (Courard et al. 2014). Surface preparation, also known as surface treatment techniques, includes wire brushing, sand blasting, shot blasting, chipping, and hydrodemolition. These techniques are frequently used to remove weak layers of concrete. Techniques such as chipping with a pneumatic hammer are presently not adequate because they will induce the occurrence of microcracking on substrate (Silfwerbrand et al. 1998; Julio et al. 2004). According to previous studies (Tayeh et al. (2012, 2013a-b and, 2014), UHPFRC shows excellent interlocking with the surface of the NC substrate and results in high bond strength. Considering that the surface of each substrate is different, the bond strength varies depending on the type of surface preparation. Therefore, the bond strength between UHPFRC and the substrate depends on the surface treatment of the substrate. The highest bond strength is achieved for the sand blasted surface.

In 2005, the effects of test methods and surface roughness on the bond strength between concrete and repair material were studied (Silfwerbrand, 2013). Two types of substrates possessing different surfaces, namely, low and high roughness, were prepared. Rough surface preparation leads to higher bond strength, which increases the range between 9% to 25% for pull-off and slant-shear tests. The influence of surface roughness is more substantial when cementitious repair materials are used. Santos et al. (2012) stated that roughness is the key parameter in the behavior of concrete-to-concrete interface. The conducted experiment revealed that when fresh concrete is casted against a hardened substrate, the improvement the surface roughness contributes significantly toward bond strength.

4.2 Substrate Surface Moisture Condition

Over the years, debates on the effects of substrate surface moisture condition on bond strength are still ongoing. Questions on whether the substrate surface moisture condition actually plays an important role and the most optimum substrate surface moisture condition remain unclear. Silfwerbrand (2013) stated that surface moisture condition does not play a major role in the bond strength of a repaired specimen. Zhu (1992) has found experimental signs of optimal moisture, but the moisture influence on the bond is very small. Thus, discerning between moisture influence and scatter of the test results is difficult. However, these findings contradict the results of other studies.

The moisture condition of the substrate surface has an influence on bonding and failure mode. According to the test results, the most favorable moisture condition is SSD, which results in higher bond strength (Bissonnette et al. 2008). According to Beushausen (2010) a dry substrate absorbs the water from the overlay material, thereby resulting in the formation of a harsh mix that cannot provide a proper interlocking mechanism at the interface between the overlay and the substrate. Luković et al. (2012) found that dry substrate produced higher strength in the slant-shear test than SSD if the substrate is sufficiently roughened. When the repair material is applied to the dry substrate, it experiences significant microstructural changes, which include densification of repair material adjacent to the dry substrate. This densification clearly explained the observation of a previous study Bentz et al. (2018) on the high strength obtained during the slant-shear test. However, for pull-off testing, SSD conditions results in better bond strength than dry conditions. This result is due to enhanced hydration in the interfacial region between the repair material and SSD. In addition, a result suggested further detailed engineering on the fluidity of repair material, substrate surface roughness, and substrate moisture condition to achieve maximum bonding performance under tensile loading.

5. Conclusion

Previous studies proved that UHPFRC is suitable to be used as a repair material because it can also bond properly with substrates and make the repair system work. Concrete can be repaired due to its high degree of fire resistance. Repair is preferable compared with demolition as it is more cost-effective. The low permeability of UHPFRC also provides extra protection for the damaged substrate. The excellent performance of UHPFRC makes it suitable in rehabilitation work, especially for fire-damaged concrete. Good bond strength between UHPFRC and the substrate also indicates that it is a superior repair material. However, a universally good repair material does not exist. Different repair materials are available for different purposes, conditions, and environments. As high temperature will cause concrete degradation, repairing methods may vary. Therefore, developing efficient rehabilitation techniques that enable fire-damaged structures to be restored faces challenges. Proving that UHPFRC can also be used as a repair material, particularly for fire-damaged concrete structures, is necessary.

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