Review of Repair Materials for Fire-Damaged Reinforced Concrete Structures

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Abstract: Reinforced concrete (RC) structures perform well during fire and may be repaired after the fire incident because their low heat conductivity prevents the loss or degradation of mechanical strength of the concrete core and internal reinforcing steel. When an RC structure is heated to more than 500 °C, mechanical properties such as compressive strength, stiffness, and tensile strength start to degrade and deformations occur. Although the fire-exposed RC structure shows no visible damage, its residual strength decreases compared with that in the pre-fire state. Upon thorough assessment, the fire-damaged RC structure can be repaired or strengthened, instead of subjecting to partial or total demolition followed by reconstruction. The structure can be repaired using several materials, such as carbon fiber-reinforced polymer, glass fiber-reinforced polymer, normal strength concrete, fiber-reinforced concrete, ferrocement, epoxy resin mortar, and high-performance concrete. Selecting an appropriate repair material that must be compatible with the substrate or base material is a vital step to ensure successful repair. This paper reviews existing repair materials and factors affecting their performance. Of the materials considered, ultra-high-performance fiber-reinforced concrete (UHPFRC) exhibits huge potential for repairing fire-damaged RC structures but lack of information available. Hence, further studies must be performed to assess the potential of UHPFRC in rehabilitating fire-damaged RC structures.

1. Introduction

Reinforced concrete (RC) exhibits fire resistance as a result of its low heat conductivity that prevents the loss or degradation of the mechanical strength of concrete core and internal reinforcing steel; RC exhibits lower heat conductivity of about 1.6 W/mK than that of steel (45 W/mK), according to EN1994-1-2 [1]
and EN1993-1-2 [2], respectively. According to EN1992-1-2 [3], the conductivity of concrete decreases as the surrounding temperature increases. Under prolonged exposure to high temperatures, the mechanical strength of concrete and the properties of steel reinforcement bar inside it would reduce. Chan et al. [4] reported that the compressive strength of concrete may reduce up to 50% when the concrete is exposed to 600°C. At 800°C, the residual compressive strength of the concrete is only 20% of the original value. Furthermore, normal-strength concrete experiences a sharper loss in tensile splitting strength than compressive strength at 600°C. Exposure to high temperatures may also change the pore structure of concrete through pore structure coarsening, which leads to increased permeability but reduced durability of the concrete. After exposure to 600°C, the cumulative pore volume in normal-strength concrete increases twice. At temperatures higher than 600°C, extreme C-S-H gel dehydration and pore structure coarsening contribute to the strength loss of the concrete [4]. Fires in concrete structures rarely result in serious global structural damage, and most of the damaged structures can be successfully reinstated. Therefore, repair of fire-damaged concrete structures is a more viable and economical option than demolition and rebuilding [5,6].

Various materials and methods can be used to rehabilitate fire-damaged RC structures. As such, appropriate repair materials and techniques must be selected. Repair materials must have good bond strength with the substrate and restore the original bearing capacity and fire resistance of the RC structures, considering that a second fire cannot be ruled out [7]. Moreover, repair techniques must involve least interventions to reduce the cost due to delayed use of the facilities. This paper discusses different repair materials such as fiber-reinforced polymer (FRP), glass fiber-reinforced polymer (GFRP), carbon-fiber reinforced polymer (CFRP), normal strength concrete (NSC), fiber-reinforced concrete (FRC), shotcrete, and ferrocement. This paper also elaborates available repair techniques for applying these materials and their corresponding performance.

2. Repair Materials and Methods
Selecting an appropriate repair material is a critical step in repair process. Repair materials must be compatible with the base material, project needs, available technical resource, financial constraint, and other specific requirements of the project [8]. In general, repair materials should be similar to the original construction material. In a previous study, NSC was used to repair fire-damaged concrete members. Lin et al. [9] investigated the behavior of RC columns repaired with cast-in-place NC after being damaged by fire. However, the performance of NC as repair material for fire-damaged concrete structures has been rarely investigated.

Shotcrete is a cementitious material used by engineers to repair fire-damaged RC members [8]. In contrast to NC, the use of shotcrete omits the need for formworks and the time for their construction and the need to pump and consolidate the concrete in relatively blind formworks. Shotcrete exhibits short setting time and high early-age mechanical properties; this material is a popular choice for various applications, such as tunnel support, rapid repair, slope support, gas and oil wells, and other underground structures [10]. Prugar et al. [11] used shotcrete to repair fire-damaged RC joist of high school buildings. Gosain et al. [8] used shotcrete to repair fire-damaged RC slab and joist of a stadium. Epoxy resin mortar is another commercial cementitious material that does not require formworks and is easy to apply to damaged RC members. Yaqub and Bailey [6] used epoxy resin mortar to repair RC columns severely damaged by fire. However, data on the performance of shotcrete and epoxy resin in repairing fire-damaged concrete structures remain limited.

Yaqub et al. [12] and Haddad et al. [13] used another cementitious material, namely, ferrocement, which consists of wire meshes and mortar, to repair fire-damaged RC structures. Applying ferrocement is labor intensive, but the workmanship required to construct it is quite low and the raw materials are locally available. Repairing structures using ferrocement is cheap and ideal for residential buildings in developing countries, such as Malaysia. Although ferrocement is fairly an old technology and has been used as a
construction material for more than 50 years [14], its application in repairing fire-damaged RC members is limited and has been rarely reported. Ferrocement is a highly-versatile RC material that can be used to effectively wrap structural members with various cross sections; as such, this material exhibits considerable potential for structure repair. The strength of ferrocement depends on two factors, namely, sand to cement ratio and quantity of reinforcing material (wire mesh). However, the use of ferrocement requires installation and tying of rods and mesh together, and these processes are tedious and time consuming. Therefore, ferrocement is not recommended to be used as repair material for commercial buildings and bridges because of time constraint and economic implications. A large amount of time required to repair these facilities will increase the financial burden by the owner and users.

CFRP and GFRP, in either plate or sheet types, are the most popular materials used to repair defective RC structures [5, 6, 15 - 19]. The advantages of these materials include ease of application, high strength to weight ratio, excellent mechanical strength, and resistance to corrosion and chemical attack. These materials also exhibit low density, which is important because they add less weight to the repaired structure and can be conveniently applied without using heavy machineries. The tensile strength of CFRP and GFRP is extremely high, which is about three to eight times higher than steel reinforcements in RC (Table 1). FRP exhibits lower density than concrete and steel (Table 1), and the thickness of FRP plate and sheet is around 1.5 and 0.17 mm, respectively, which is very low; hence, FRP can be conveniently applied without requiring heavy machineries to handle and install it to the structure. FRP is also suitable to structures of various geometry types or cross section. Yaqub and Bailey [5] showed the more effective confinement of FRP sheet for fire-damaged circular cross section RC column than for square column.

In current concrete technology development, fibers are introduced into concrete mixtures to overcome the limitations of low tensile strength and brittle failure of plain concrete. Many types of fiber can be used, and steel fiber is the most popular choice. Steel fiber-reinforced concrete (SFRC) is a suitable candidate for repairing fire-damaged RC members. Haddad et al. [20] explored the effectiveness of using SFRC to repair fire-damaged RC slab.

Recent advancement in SFRC has resulted in the development of UHPFRC, which is a cementitious material with higher compressive strength (> 150 MPa), tensile strength (>10 MPa), and ductility than NC. UHPFRC can be fabricated by adding fine aggregates, steel fibers, and water-reducing agent into the concrete mixture with a low water-cement ratio (<0.2). The actual maximum value of the compressive strength of cast in place UHPFRC is 115 - 120 MPa [21]. Compressive strength is not the primary feature of UHPFRC because tensile properties are often more important, especially for rehabilitation work or cast-on-site application. UHPFRC exhibits not only high tensile strength (>10 MPa) but also strain-hardening properties. According to Naaman and Reinhardt [22], strain hardening occurs when tensile strength \( \sigma_{pc} \) exceeds cracking stress, \( \sigma_{cc} \). This property may prevent the formation of shrinkage cracks due to different expansion properties between the old and new concrete-based materials. Hence, UHPFRC is a suitable candidate material for repairing structures. Moreover, UHPFRC exhibits higher density and lower porosity, resulting in improved durability, than ordinary concrete or high-performance concrete (HPC). For instance, Charron et al. [23] revealed that the equivalent water permeability of UHPFRC with residual tensile deformation until 0.13% is similar to that of uncracked NC. As a result, no carbonation, chloride ion ingress, or sulfate reaction occurred because the material is waterproof. Therefore, the use of UHPFRC will protect steel bars against corrosion [24].
Table 1. Comparison of concrete, CFRP and GFRP properties [5-6, 15-19]

| Material       | Concrete | Steel | CFRP         | GFRP        |
|----------------|----------|-------|--------------|-------------|
| Tensile Elastic Modulus (GPa) | ≈25      | ≈180  | 165– 238     | 76          |
| Tensile strength (MPa) | 3-6      | 500   | 2,700-4,100  | 1,518-2,300 |
| Density (kg/m³) | 2,240– 2,400 | 7,850 | ≈1,500      | ≈1,800     |

Selecting a suitable method for repair depends on the type of affected RC member. For flexural members, such as slabs and beams, the repair material is either applied at the soffit or tensile side only or to the soffit and side surfaces. Scholars have also attempted to apply the repair material at the compressive side (top surface), but the effect is insignificant [25]. For compressive members, such as columns, jacketing method is employed, regardless of the type of repair material.

3. Factors Affecting the Performance of Repair Material

Several factors affect the performance of repair materials. First, the damage severity of the post-heated RC members affects the performance of repair materials. Yaqub and Bailley [5] reported that RC columns heated up to 500 °C experienced two different types of damage, namely, crack and crack with significant spalling. The load carrying capacity of column that experienced significant spalling repaired with epoxy resin and wrapped with GFRP sheet, increases only up to 110% of the original capacity. Meanwhile, for the fire-damaged RC columns without significant spalling and repaired with GFRP only, the load carrying capacity increased up to 129% of the original capacity.

Another critical factor that influences the performance of repair materials is the bond strength between the repair material and the old material [26, 27]. In general, concrete-based repair materials exhibit good bond strength with the old concrete material; nevertheless, the bond strength between the old concrete substrate and other materials, which are bound with agents, such as epoxy, should be considered. Toutanjii and Gomez [19] reported that concrete beams repaired with FRP subjected to wet/dry conditions showed worse performance caused by epoxy degradation than those kept at room temperature. Hence, FRP is unsuitable to be used in regions with hot climate, such as Malaysia. Farhat et al. [28] observed no bond degradation between UHPFRC used as repair material and concrete beam under thermal cycling test. Yaqub et al. [12] reported that ferrocement exhibits good bond with fire-damaged concrete and observed no debonding between the ferrocement jacket and the damaged substrate.

The bond strength between the cementitious material and the old concrete substrate depends on the surface treatment method used and the surface condition of the substrate. Surface treatment is used to clean the surface from loose materials and dust, which may jeopardize the interface bond strength between the repair material and the substrate. Tayeh et al. [29] found that sand blast method is the optimal surface treatment method. Baharudin et al [30] suggested that the substrate surface should be wetted with water prior to applying repair materials. In the works of Tayeh et al. [29] and Baharudin et al. [30], UHPFRC with steam curing was used as repair material; however, this method is impractical and costly and should
be replaced by cast-in-place UHPFRC for repair works [31]. The bond strength between cementitious repair material and fire damaged concrete substrate also depend of the maximum temperature experienced by the substrate. Recent study found that, the bond strength decrease as the heat temperature experienced by the substrate increases [32]. Therefore, the bond strength of cast-in-place UHPFRC and fire-damaged concrete must be further investigated.

Cross-section shape also plays a vital role in increasing the strength of fire-damaged RC members, primarily, the column. Yaqub and Bailey [5] found that fire-damaged circular cross-section wrapped with FRP exhibits increased axial strength and ductility than the square cross-section. This finding could be attributed to the fact that square cross sections contain ineffectively confined concrete regions and intensification of stresses at their corners, whereas circular cross sections contain fully effective confined concrete regions with FRP jackets.

The performance of repair materials, such as FRP, depends on the type of structural members to be repaired (i.e., either flexural or compression member). Haddad et al. [20] used FRP to repair fire-damaged RC slab and found that FRP improves the stiffness but fails to improve the ductility of the slab. Other studies that used FRP to repair fire-damaged RC columns indicated that FRP can improve the ductility but fails to restore the stiffness of the column [5, 6, 12, 15, 33]. Therefore, the behavior of FRP in strengthening flexural and compression governing members must be further investigated.

Proper curing method may positively affect the performance of repair materials, primarily cementitious materials. Curing of fire-damaged concrete substrates may also improve the mechanical properties, such as compressive strength and stiffness, of repair materials. Haddad et al. [20] showed that water curing significantly recovered the compressive strength and modulus elasticity of fire-damaged concrete cylinder at about 30% and 60%, respectively, of the undamaged samples. A similar study reported the significant effect of curing on the stiffness of the investigated RC slab; that is, the stiffness of fire-damaged RC slabs increased by 56%. Therefore, fire-damaged substrates should be water cured after removing all loose substances prior to applying repair materials.

4 Findings of Previous Works
In general, repair materials are considered effective if they can improve the original capacity (i.e.: strength, stiffness and ductility) of fire-damaged RC members or structure systems. Studies reported that FRP may increase the strength, ductility, and energy dissipation of fire-damaged concrete up to or more than the original capacity [5, 6, 12, 15, 33]. However, FRP fails to improve the elastic stiffness of the fire-damaged concrete members due to the huge difference in the strength-to-weight ratio or stiffness between FRP and the concrete material. Scholars have attempted to overcome this problem by increasing the stiffness or FRP confinement via increasing the thickness of the material; this method slightly increased the column stiffness but adversely affected the ductility of the repaired column [15]. Haddad et al. [13] used two CFRP layers to repair fire-damaged RC beams and found that the stiffness can be restored up to 160% of the original undamaged sample; however, the repaired samples exhibit brittle failure. Furthermore, Yaqub et al. [12] found that ferrocement is more effective than FRP in improving the stiffness of fire-damaged concrete members but it cannot restore the original stiffness of the member. This finding may be partly due to the increased cross-sectional area after ferrocement jacketing. Haddad et al. [20] reported that SFRC may restore the original stiffness of fire-damaged RC slab but cannot restore the load carrying capacity. Therefore, ferrocement or SFRC should be combined with FRP for repairing fire-damaged concrete members to restore their original strength, ductility, and stiffness. Hence, the potential of the composite materials of FRP and SFRC or ferrocement for repairing fire-damaged RC members must be assessed in future studies.
Li et al. [9] found that fire-damaged RC columns repaired with fresh cast-in-place NSC could attain their original or even higher strength and stiffness than those of the undamaged columns but cannot improve the ductility. The ductility of structural members is important to evaluate the performance of a structural system subjected under extreme loading [12]. Under this condition, the ductile structural members will show signs, such as crack and deformation, before failure. The building occupants or facilities’ users should be warned to give time for them to leave the facilities. In comparison with normal concrete, shotcrete is preferred as repair material for fire-damaged concrete members because it omits the requirement of formwork and compaction work. Few studies have successfully used shotcrete for repairs [8, 11]. Although the mechanical properties of shotcrete and normal concrete are identical [34], the high velocity pressure during placing of shotcrete makes it relatively denser than normal concrete and is thus more vulnerable to explosive spalling defect under fire. Therefore, the behavior of shotcrete must be studied under fire because the repaired structure should exhibit not only sufficient bearing capacity under ordinary conditions but also an adequate fire resistance because a second fire cannot be ruled out.

Leonardi et al. [7] and Abdullah et al. [35] proposed the use of a relatively new developed concrete known as UHPFRC to repair fire-damaged RC members. In the numerical study conducted by Leonardi et al. [7], UHPFRC jacketing technique was used to repair and improve the strength of fire-damaged RC beams and columns, which were exposed to standard fire for 120 and 180 minutes. The performance of UHPFRC jacket under fire was also investigated, and the material may resist second fire up to 180 minutes. Despite these promising results, further studies on the thermal behavior of normal concrete and UHPFRC must be conducted. Kahanji et al. [36] performed an experimental study and reported that UHPFRC beams experience severe explosive spalling after being exposed to 60 minutes of standard fire. Leonardi et al. [7] also reported that the axial strength of the RC column decreased by 18% after 30 minutes of fire exposure under the standard fire curve of ISO 834 [37], which is equivalent to about 800 °C. Al-Salloum et al. [38] found that the axial strength of RC column reduced by about 60% after exposure to 800 °C; this finding is supported by other works [39, 40, 41].

The production cost of UHPFRC is three times higher than that of normal concrete due to high cement content, very fine aggregates, and additional admixtures, such as silica fume, steel fiber, and high-range water reducer [42]. The high production cost will directly affect the total cost of repair works. Scholars have used UHPFRC of different thicknesses in jacketing method (Table 2). Generally, the recovery percentage of the load bearing capacity of structural members increases with increasing thickness of UHPFRC. In the computational study by Leonardi et al. [7], fire-damaged RC members with 40 mm-thick UHPFRC recover 300% of its load bearing capacity, which is extremely high and sufficient. To optimize the cost of UHPFRC in repair works, researchers must determine the optimum UHPFRC thickness for recovering the original load bearing capacity of the repaired structural members.

The tensile properties of UHPFRC (i.e., first cracking stress, σ_{cc} and strain, ε_{cc}, elastic modulus, E_{cc}, strain hardening modulus, E_{pc}, composite strength, σ_{pc}, and energy dissipation capacity, g) significantly improved as the fiber content increased from 1.0% to 3.0% (by volume); thus far, the sensitivity of the tensile properties of UHPFRC to fiber type (i.e., smooth, twist, and hook) remains debatable among researchers [43, 44]. Haddad [13] reported that the load bearing capacity of RC beam decreased by 28% after heating at 600 °C for 3 hours. Yaqub and Bailey [5] reported that the load bearing capacity of RC columns decreased by about 45% after uniform heating to 500 °C. Table 3 shows that the load carrying capacity of existing beams increases as the tensile strength or fiber content of UHPFRC increases. In the numerical analysis conducted by Lampropoulos et al. [25], UHPFRC exhibits huge potential to recover the original capacity of fire-damaged RC members. Lampropoulos et al. [25] conducted a uniaxial tensile test on a dog bone specimen containing UHPFRC with 3% (by volume) steel fiber content; the tensile strength obtained is about 12 MPa, which was then used in numerical analysis to predict the performance of RC beams strengthened with UHPFRC. According to Wille et al. [44], the tensile behavior of UHPFRC
in dog bone size specimen may substantially differ if large specimens are used. Therefore, an experimental study must be conducted to determine the actual performance of UHPFRC with various fiber contents in improving the capacity of existing or damaged RC members.

Table 2. Thickness of UHPFRC layer used in strengthening works

| Study                           | Investigated structural member | UHPFRC Thickness (mm) | Recovering (%) |
|---------------------------------|--------------------------------|-----------------------|----------------|
| Lampropoulus et al, [25]        | Beam(existing)                  | 50                    | 300            |
| Leonardi et al, [7]             | Beam and column (fire damaged)  | 40                    | 300            |
| Martinola et al, [45]           | Beam (under designed: low      | 40                    | 200            |
|                                 | compressive strength and       |                       |                |
|                                 | reinforcement ratio)           |                       |                |
| Farhat et al, [28]              | Beam (under designed in        | 16                    | 145            |
|                                 | flexural)                      |                       |                |

Yaqub and Bailey [5] and the present study indicated that cross section influences the performance of repair materials. As such, the performance of UHPFRC in rehabilitating RC members with different geometries or cross section must be determined. To the best of authors’ knowledge, only Leonardi et al. [7] investigated the potential of using UHPFRC to repair fire-damaged RC columns and considered square columns in the numerical analysis. Therefore, further experimental works must be conducted to assess the actual performance of UHPFRC in repairing RC members of different geometries and cross sections.

Table 3. Tensile strength of UHPFRC and its performance in improving load bearing capacity of existing RC beams [25]

| Tensile Strength (MPa) | Increment (%) |
|------------------------|---------------|
| 8                      | 119           |
| 12                     | 200           |
| 16                     | 244           |

5. Conclusion
Selecting appropriate materials for repairing fire-damaged RC members is a crucial task. Repair materials must be compatible with damaged concrete substrate and must restore the original capacity of damaged structural members or systems. This paper reviews materials that can be used to repair fire-damaged concrete. These materials include CFRP, GFRP, FRC, ferrocement, epoxy resin mortar, and UHPFRC. Based on the information presented in this paper, the following conclusions are drawn:
Engineers prefer to use shotcrete as repair material because it omits the need for formworks, the time to construct formworks, and the need to pump and consolidate the concrete in relatively blind formworks. However, limited data are available with regard to the performance of shotcrete in repairing fire-damaged RC members.

Previous studies investigated the potential of using CFRP and GFRP, which can restore the load carrying capacity and ductility of fire-damaged RC members but fail to improve their stiffness.

FRC and ferrocement may improve the stiffness of fire-damaged RC members but cannot restore the load carrying capacity and ductility.

Epoxy resin exhibits good bond strength with fire-damaged concrete but cannot improve the capacity of fire-damaged RC members.

UHPFRC has a set of special traits, such as exceptional durability, outstanding mechanical properties, and ease of application, making it a potential candidate for successful repair of fire-damaged RC structures. Leonardi et al. [7] performed a numerical study to explore the potential of UHPFRC. However, few aspects, such as fire behavior, of NSC and UHPFRC must be further clarified through experimental works to determine their actual performance. Additional parameters, such as fiber content, UHPFRC thickness, and geometry of fire-damaged RC members, should also be evaluated to comprehensively explore the potential of UHPFRC as a repair material for fire-damaged RC members.

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