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REVIEW ARTICLE

Repairing Materials for Different Post Fire - Damaged Structural Concrete Members: A Critical Review

A. A. Abdalla[1] and F. R. Karim[2,*]

[1]M.Sc. student, Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaimani, Iraq.
[2]Lecturer, Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaimani, Iraq.

ABSTRACT – When concrete structures are exposed to elevated temperatures or fire, their strength begins to degrade. The major problem is that the structure induces cracks, which let the aggressive material enter the concrete and the steel reinforcement corrosion. Therefore, the damaged member should have been strengthened or repaired; sometimes, the repair is chosen over demolition because it is more economical. Researchers used materials to repair heat-damaged concrete, such as fiber-reinforced polymer (FRP) composites, shotcrete, ferrocement, epoxy resin mortar, and fiber-reinforced concrete. The compatibility of these materials should be investigated, for example, the bond strength between repair material and substrate. Ferrocement can restore stiffness and toughness, while a structure with FRP jacketing cannot regain stiffness. Reviewing post-fire strength and repairing materials has not been done; therefore, this study highlights the strength loss of fire-damaged concrete and the repaired structure's confinement.

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INTRODUCTION

Concrete is widely used in construction due to its low heat conductivity and steel reinforcement protection [1]. The compressive strength of concrete can decrease by up to 50 percent if the concrete is exposed to 600 °C. When concrete is exposed to fire for a long period, the concrete strength is reduced [2, 3]. Also, the reinforcement steel strength inside the concrete was reduced [4]. Concrete structures will deteriorate in several ways, such as chemical, physical, electrochemical, accidental fire, or combination [6]. The deteriorated concrete should be repaired with appropriate material. Those materials should have desired properties such as compatibility with the base material, low price, and low shrinkage [5]. Composites have been established in recent years as a successful enhancement approach, such as glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP), which have a high strength-to-weight ratio and are non-corrodible. The installation process will be easy since they have a lightweight [7]. In recent studies, the effect of fire on the strength of concrete structures has been studied, and the repairing materials used in restoration by different authors have been investigated. On the other hand, the effect of fire duration and its temperature on the damaged concrete was considered. This review focuses on the repair materials and the method for applying them to the substrate; the strength of damaged concrete and the improvement of toughness and stiffness were evaluated. Thus, the mechanical properties of damaged concrete by fire were dramatically dropped; therefore it is very important to improve these properties.

SIGNIFICANCE OF RESEARCH

Due to the reduction of the mechanical properties of concrete while the structural elements subjected to fire. This paper highlights the evaluation of the materials used to repair different structural fire-damaged concrete members and compares their effects on the restored concrete's mechanical properties and the measurement of their efficiency.

REPAIRING MATERIALS FOR DIFFERENT STRUCTURAL MEMBERS COMPRESSION MEMBERS

Al-Nimry et al. [8] repaired concrete columns damaged by the effect of heating with carbon fiber reinforced polymer (CFRP) as a repair material, thirteen samples were cast, and eleven of them were subjected to 500°C for 3 hours, nine samples of the heat damaged group were repaired by using seven different repairing arrangement of CFRP (Figure 1).

In this experiment, the following points were examined:

1. Wrapping sheet thickness.
2. Configuration of wrapping.
3. Using CFRP plate as longitudinal reinforcement bonded externally and plate area as well.

When concrete is exposed to the heat of 500 °C, the deflection under applied load increases and the ultimate load carried by the column decreases by more than 50 % of its original strength; however, the toughness of the samples

*CORRESPONDING AUTHOR | F.R. Karim | ✉ ferhad.karim@univsul.edu.iq

increased by 20 %, as shown in Figures 2 and 3. For samples repaired with CFRP plate and sheet, the increase in ultimate strength and toughness compared to control samples is summarized in Table 1.

Table 1 shows the percent of the estimated load of the repaired specimen compared to the original specimen. The repaired samples' maximum deflection, ultimate load, and toughness are compared in Figure 2 to Figure 4. As presented, fully wrapping the column using a plate has a good restoring of the load carrying capacity other than other types, which is 83% of the control samples load caring capacity. The sample that was fully wrapped with two layers had a higher toughness when compared with the other samples.

Table 1. Comparison of the original to restored sample ultimate load and toughness.

Designation	**Number of wrapping layer**	**Ultimate load repaired / Ultimate load original (%)**	**Toughness repaired / Toughness original (%)**
C-H	Control	45	122
WP1	1, partially	48	71
WP2	2, partially	38	85
WF1	1, fully	54	236
WF2	2, fully	68	415
WF1-PL-1.4	plate ρ_p = 1.4, partially	83	187
WF1-PL-2.1	plate ρ_p =2.1, partially	78	75
WP1-PL-1.4	plate ρ_p = 1.4, partially	72	84

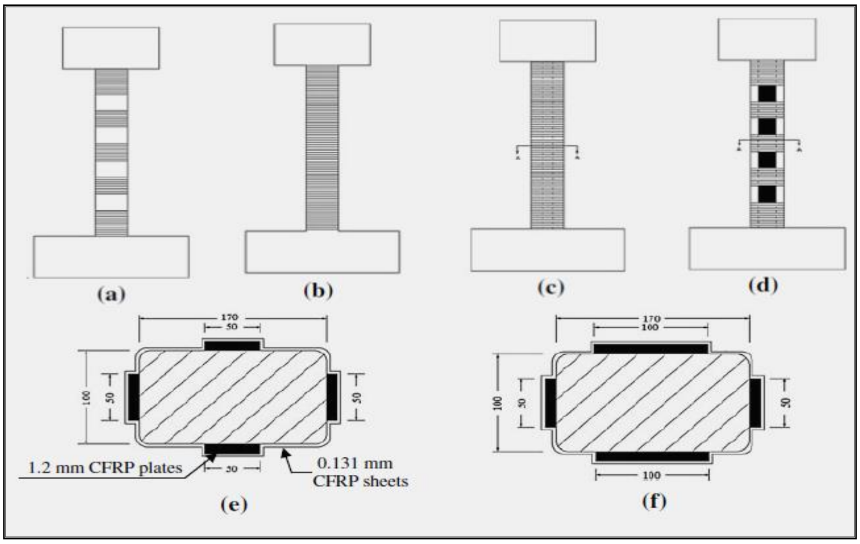

Figure 1. Arrangement of CFRP sheets and plates, (a) partially wrapped, (b) Fully wrapped, (c) Full wrap with straps, (d) Partial wrap with straps, (e) Repaired specimen cross-section with 1.4% strap, d. Repaired specimen cross-section with 2.1% strap.

Finally, CFRP can improve the repaired sample's strength and toughness by up to 83 % and 415%, respectively. The member's capacity to carry the load with full wrapping and plate is higher than the other application method. Bisby et al. [9] investigated strengthening a heat-damaged short column covered with CFRP (Figure 5) wrap to evaluate the influence of using this material to regain the damaged specimen's strength. The 33 samples were prepared and tested while these parameters were considered:

a) Fiber-reinforced polymer (FRP) presence
b) Duration of heating
c) Temperature of heating

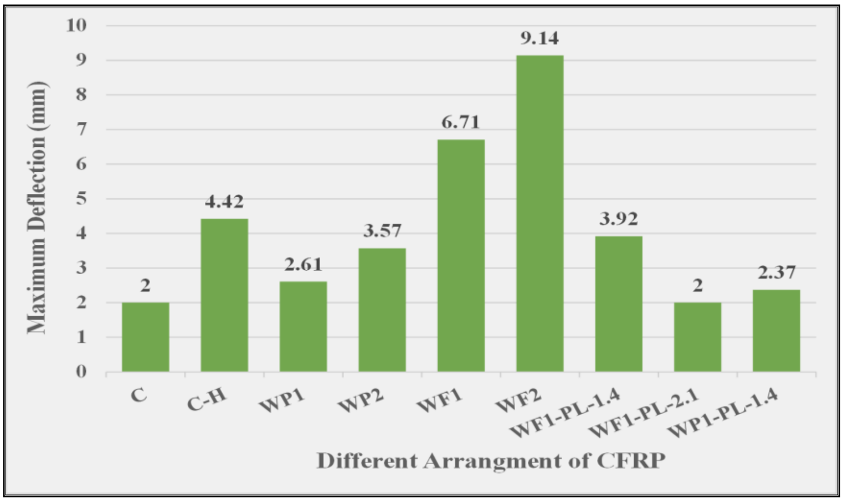

Figure 2. Deflection of the columns with a different arrangement of CFRP.

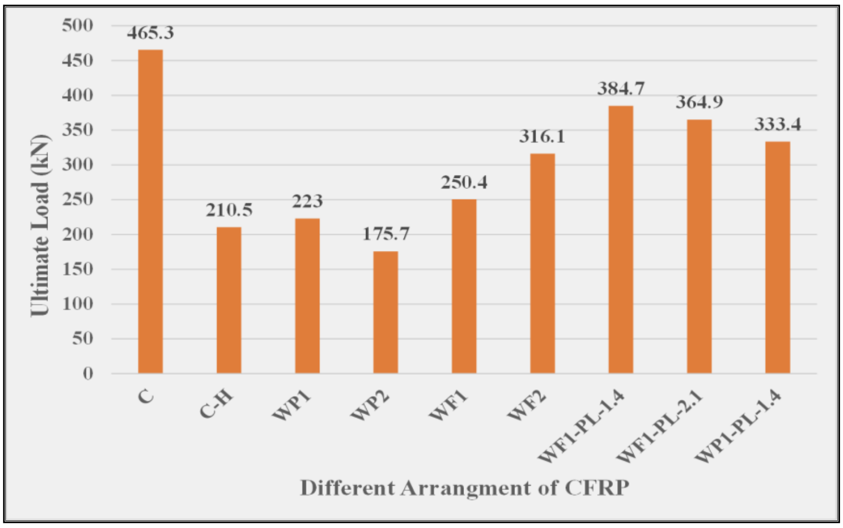

Figure 3. Ultimate Load of Control Samples and CFRP Repaired Samples.

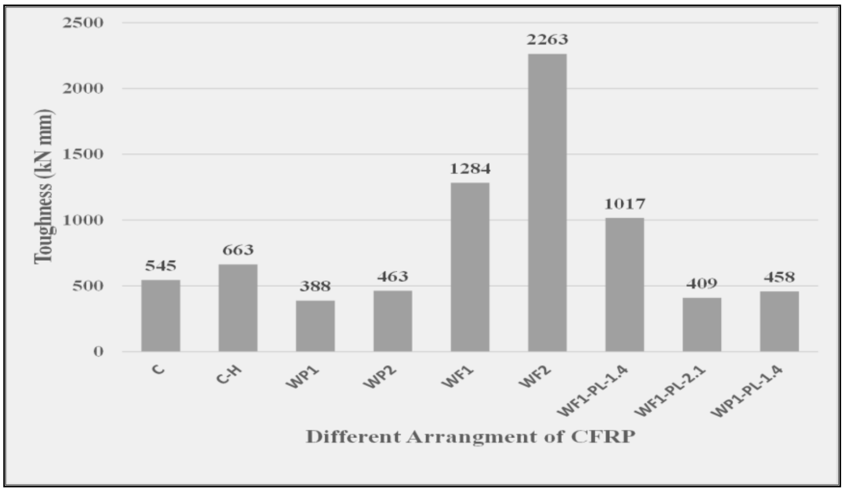

Figure 4. The toughness of the columns after exposure to high temperature and after repairing with CFRP.

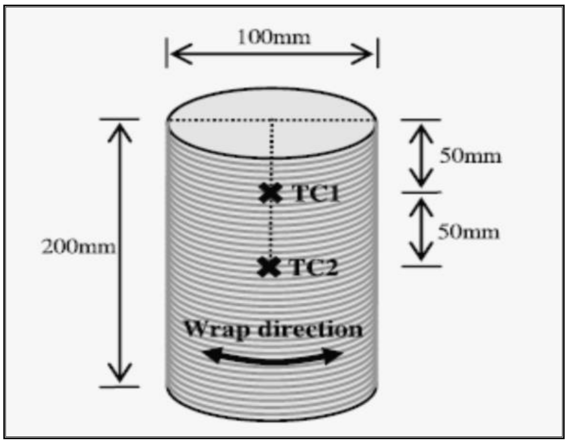

Figure 5. The layout of FRP and position of thermocouples [9].

The author measured the concrete strength after exposing concrete for 120 and 240 min at 300, 500, and 686 °C. When the sample was heated for only 120 minutes at 686 °C, the strength of the samples decreased to fewer than 60 %. However, there was an increase in the strength after the sample was confined with FRP wrap. The load-carrying capacity of the strengthened samples was greater than the heated control sample, and the confinement ratio was 180 to 210%. Ferrocement and FRP Jacketing (Figure 6) with epoxy resin mortar were used by Yaqub et al. [10], and the influence of using these materials on compressive strength and stiffness was evaluated. Sixteen specimens were cast, eight square, and other samples were circular. Specimens heated at 500 °C then tested the result of the experiments then reported such as the following; the axial compressive strength of concrete is improved, and the FRP jackets increased post-heated reinforced concrete columns' strength. Ferrocement jacketing significantly enhanced the strength and stiffness of post-heated reinforced concrete columns. However, the FRP jacket, relative to the ferrocement jackets, does not contribute to restoring the stiffness of the reinforced heat-damaged concrete columns.

Figure 6. Repairing procedure application of (A) Ferro cement, (B) FRP jacketing [10].

Compared to the ferrocement jacket post-heated columns under similar axial load effects, the FRP jackets exhibit a significantly developed energy dispersion capacity. This is due to the after-heating columns' achievement restored with FRP jackets with enhanced strength and toughness. The relative strengthening effect of using FRP or ferrocement jackets on circular columns was greater than on square columns. This may be because the FRP or ferrocement jackets for circular column shapes were subjected to hoop tension, and the concrete cores of circular columns were subjected to uniform radial compression, thus creating uniform passive pressure of confinement. In contrast, the lower reinforcement effect for square parts is possibly due to the transmission of high confining pressure/stress concentration at the corners, resulting in a lower failure load for the FRP or Ferro-cement jackets relative to the sides. Lenwari et al. [11] experimented with using FRP sheets for after-fire restoration of concrete strength under different situations such as:

1) Full and Partial wrap
2) Water-cooled and air-cooled samples
3) Different temperature
4) Duration of heating

The heating temperature was 300 to 700 °C at an interval of 200 °C. The author had shown that the duration of the fire, its temperature, strength before confinement, and cooling of the samples affected the post-heated specimens. The samples were categorized into three groups, and the author used three different strengths in this experimental program. The results showed that low-strength concrete is more vulnerable to the degradation of fire-induced residual properties than high-strength concrete. After repairing concrete exposed to high temperatures, CFRP wrapping will vastly increase its strength and ductility. In addition, the enhancement of strength by CFRP for fire-damaged concrete is higher than that of undamaged concrete. A different material, hybrid fiber-reinforced polymer (HFRP), was used through an experiment by Chinthapalli et al. (2020) [12] to understand the efficacy of the retrofitting technique of hybrid fiber-reinforced polymer (FRP) for the emergency repair of badly compromised RC columns under mixed fire and axial compression loads (Figure 7).

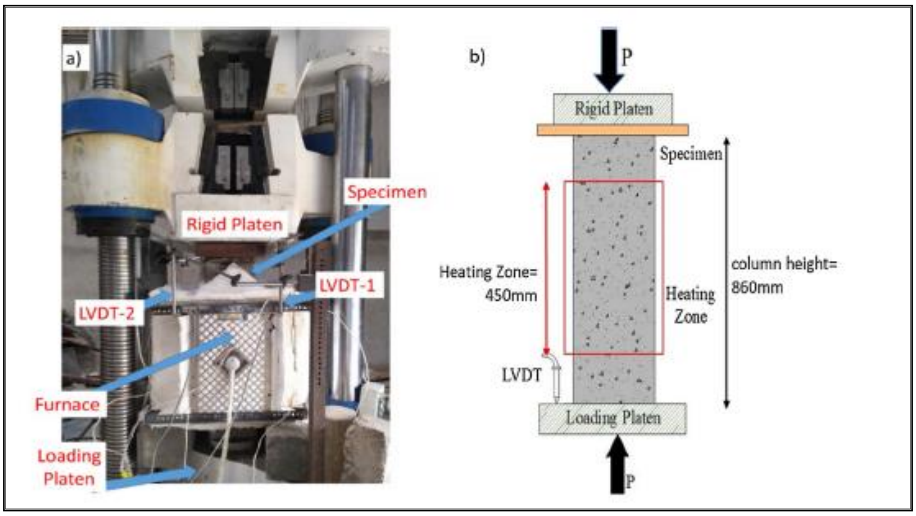

Figure 7. The experimental setup for the test [12].

In this study, the combination of near-surface mounted (NSM) and CFRP wrapping was used as confinement for fire-exposed columns, and the effect of fire and axial compression was observed. The damaged columns were covered with hybrid F to investigate the FRP retrofit method (Figure 8). Experimental outcomes showed that 71 percent to 116 percent of the initial column capacity before the fire damage was returned by the hybrid FRP retrofitting method. The results reported by the author were as follows axial strength of the whole column did not completely recover with the hybrid FRP renovation process. The compressive strength of the damaged sample was reduced due to the high temperature, and residual strength varied between 15 to 67 percent based on the column detail and heating duration. For high-strength concrete, the recovery portion of the original capacity is low. Therefore, additional research should be done to know the cause of this. When (a) Fire-damaged column, (b) Removing the concrete cover, (c) Placing formwork for grout, (d) Grooved specimen for NSM, (e) NSM braced, and (f) Hybrid FRP strengthened. In another work, Yaqub and Bailey [13] compared the strength of CFRP and glass fiber-reinforced polymer (GFRP) for Repairing usage (Figure 9). The samples were grouped into not heated, heated, and badly spalled repaired with CRFP or GFRP; reparation was such as following: the authors obtained the result and concluded that after heating at 500 °C, the strength dropped to less than half of its capacity, and the stiffness reduction was larger than the compressive strength decrease. The sample strength improvement of the seriously spalled sample, which was repaired with GFRP, and the unheated sample, which was just wrapped with GFRP, was 29 and 122 %, respectively.

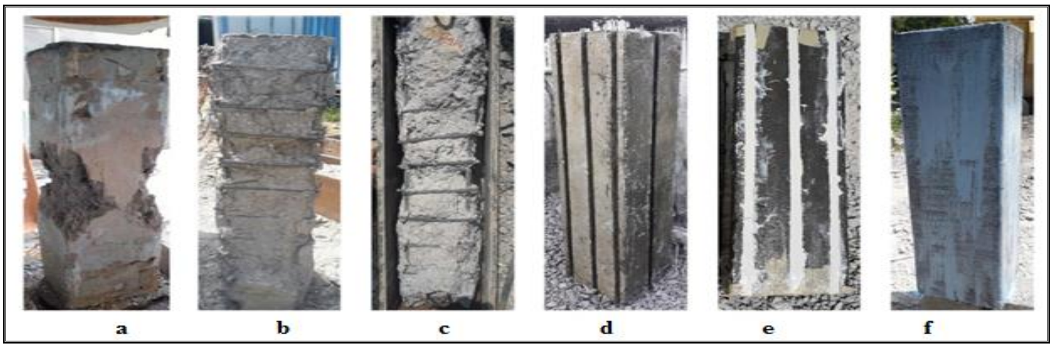

Figure 8. Procedure for hybrid FRP retrofit [12].

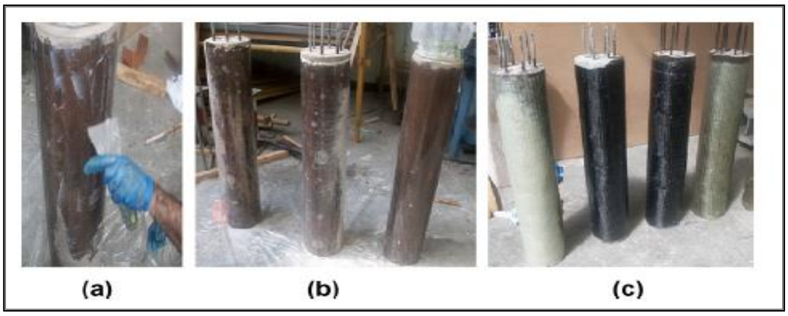

Figure 9. Procedure for hybrid FRP retrofit, When (a) Epoxy Application (b) Application of primer adhesive (c) Wrapping of GFRP and CFRP [13].

An investigation was done using ultra-high-performance fiber-reinforced concrete (UHPFRC) as a repair material for restoring fire-damaged concrete by Baharuddin et al. [14] to know the possibility of using this type of concrete to repair damaged concrete by elevated temperature, and the bond strength was studied. The results indicated that UHPFRC could be used to renovate damaged concrete from prolonged and elevated heat. The bond strength of the cementitious repair material with a concrete substrate is good because they nearly have the same properties. Furthermore, this type of concrete has low porosity; therefore, its permeability becomes low, and the durability of the repaired member then improves.

Baharuddin et al. [15] studied the bond strength of UHPFRC with normal strength concrete in another research. To evaluate the interfacial bond strength of the composite, slant shear and splitting tensile strength tests were performed. Three conditions of humidity were established other words, wet, saturated surface dry (SSD), and air-dried. The results showed that the surface condition affects the bond between UHPFRC and substrate increased if the base material moisture was high, the bond of UHPFRC yields a good bond, and this material could be used for repair of fire-damaged concrete.

FLEXURAL MEMBERS

Near-surface mounted CFRP was used in another research by Ashteyat et al. [1] for cantilever beam repair produced by self-compacting concrete (SCC), and the strip of CFRP was applied to the top of the beam because the top fiber of the beam is the portion where bending stress occurring (Figure 10). Eight reinforced cantilever beams were placed in pairs in an electric furnace.

Heating time and temperature were controlled using a control panel attached to the furnace; the samples were exposed to a temperature of 400 and 500 °C for 120 minutes. The exposure to elevated temperatures of SCC cantilever beams ended in extreme concrete cracking and lack of concrete capacity. The percentage of strength loss of the beams was 50 to 75 %. Compared to other research, SCC's strength loss, SCC's strength loss was greater than normal concrete.

After conducting the test, the heated samples showed their toughness increased, and the load-carrying capacity of the beam reduced. The ductility index of the repaired samples improved with the SNSM CFRP strip; the deflection (i.e., toughness) and the strength of the specimens are also improved. Furthermore, this technique can be used for development length problems in beams.

A concrete joist in a high school was badly damaged in a fire accident and then renovated with shotcrete by Prugar et al. [5], and the reparation was done with minimum interruption in the high-school operation in a relatively short time. Prugar et al. [5] said the shotcrete could be used to strengthen and cast-in-place concrete joist repair because it does not need formwork and the application time is less.

Figure 10. Creating grooves on the top of the beam and adding strips [1].

For the first time, an advanced basalt fabric-reinforced shotcrete method is proposed by Gao et al. [7] for strengthening the flexural strength of fire-damaged reinforced concrete slabs. In the research, nine slabs of one-way type were put in a furnace for 1 and 1.5 hours at standard fire temperature as in ISO 834 Standard. The strength restored for unaffected samples was 30 to 127 %, while for heated samples; improvement in strength was 68 to 190% after specimens were repaired by basalt fabric and shotcrete (Figure 11).

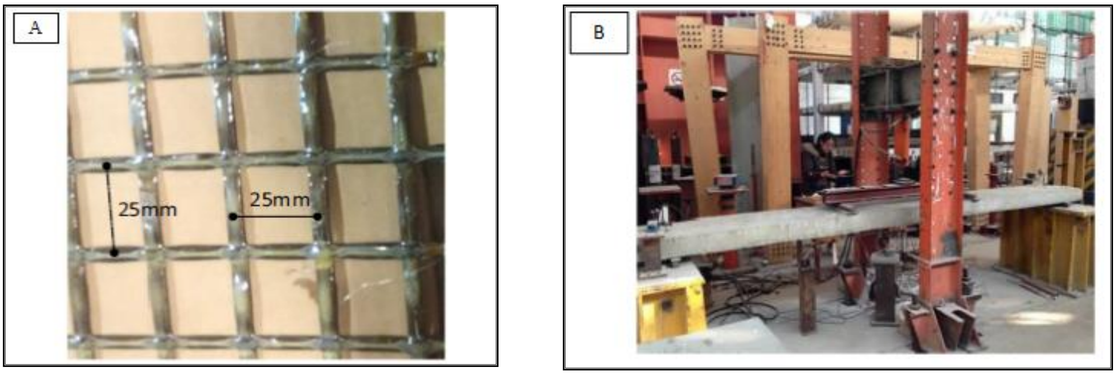

Figure 11. (A) Basalt fiber was used in this research (B), placing the sample under test.

A new technology, a high-performance fiber-reinforced jacket used for repairing purpose for fire-damaged concrete beams by Leonardi et al. [16]. Three beams were prepared for investigating the repair or strengthening. The specimens' sizes were 30 cm x 50 cm x 4.5 m. The sample was exposed to fire, and then evaluated the temperature of the fire was 700°C at different duration. The concrete was tested, and the results were as follows; instantly, the concrete strength decreased when the sample heated, but for steel reinforcement, because the concrete saved the reinforcement at the time of heating, the decrease in the strength did not occur for the first time until the temperature reached about 500°C (Figure 12).

Every building restored after being damaged by a very hot fire should have a fire-resistant greater than or equivalent to an original condition. Using ultra-high performance concrete is useful for repairing fire-damaged concrete since its compressive and tensile strengths are 180 MPa and 12 MPa, respectively.

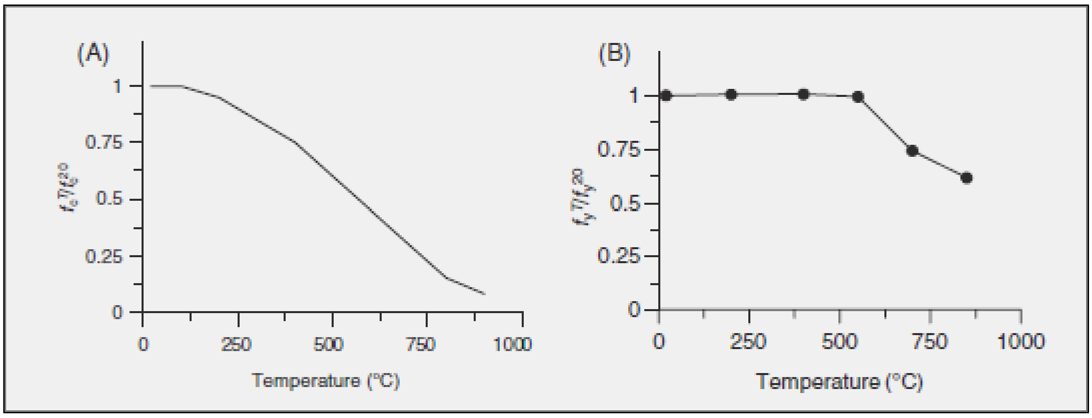

Figure 12. The ratio of unaffected sample strength to heated sample strength (A) concrete strength, and (B) steel reinforcement [16].

RESULTS AND DISCUSSION

The bond strength by the mean of splitting tensile strength of UHPFRC with normal strength concrete was compared in different moisture conditions, as shown in Figure 13.

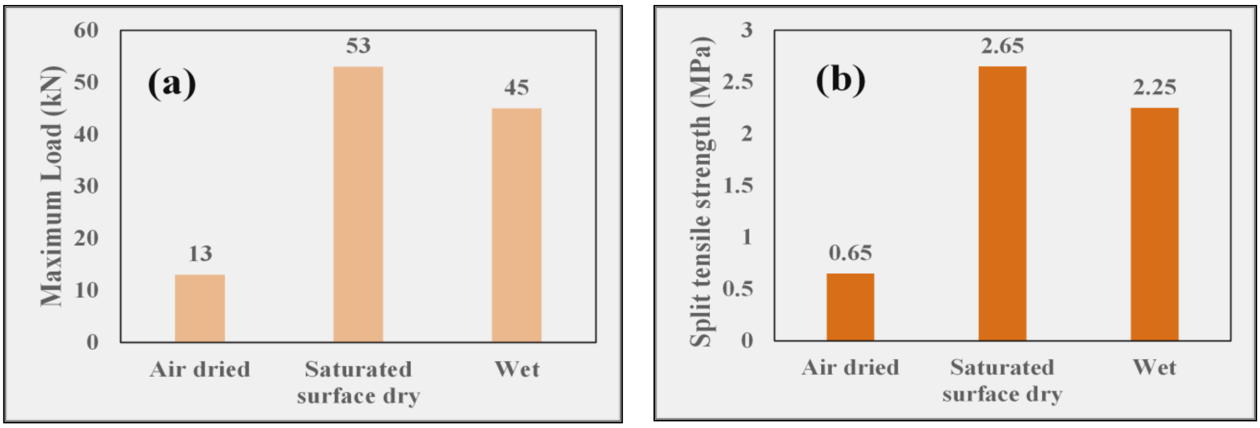

Figure 13. Comparison between (a) Maximum load and (b) Splitting tensile strength in different moisture conditions.

The maximum load carried by the sample in splitting in the air-dry condition is smaller than in other conditions, 13 kN, 25%, and 28% of saturated surface dry and wet conditions, respectively. From that, it can be concluded that when applying UHPFRC to normal strength concrete, the surface in saturated surface dry is better. Also, in wet conditions, the load-carrying capacity is high enough. The bond strength between UHPFRC and normal strength concrete increases with the substrate moisture content; however, the bond strength decreases if the substrate surface is wet.

From Figure 14, the comparison between three different materials, namely CFRP, GFRP, and ferrrocement, is conducted. It can be seen that the axial load-carrying capacity for CFRP is 1680 kN which is 85% of the non-heated and non-repaired sample and 151% of the heated sample. For GFRP, the axial load is 1396 kN which is 71% of non-heated and non-repaired samples and 126% of heated and non-repaired samples, respectively. By using ferrocement for repairing, the axial load is 1532 kN, which is greater than GFRP and smaller than CFRP, and it is 78% of the axial load-carrying capacity of non-heated and non-repaired samples and 138% of the heated and non-repaired samples. The effective material for restoring the load-caring capacity is CFRP, which had a better result.

Evaluation of the restored stiffness of the repaired sample shown in Figure 15 can be seen the figure the stiffness of the non-heated and non-repaired samples is 3854 kN/mm, and the stiffness of the repaired samples with CFRP, GFRP, and ferrocement is 564, 859, 1826 kN/mm, respectively. It can be seen here that the effectiveness of using ferrocement is higher than the two other materials.

Ferrocement can restore stiffness and load caring capacity 78 and 47% of the control sample's load-carrying capacity and stiffness, respectively; on the other hand, CFRP can restore caring load capacity to 85% while restoring stiffness up to 15% of the control sample's stiffness. GFRP, compared to CFRP, is better in restoring stiffness, while CFRP and ferrocement, the load-carrying capacity, is smaller.

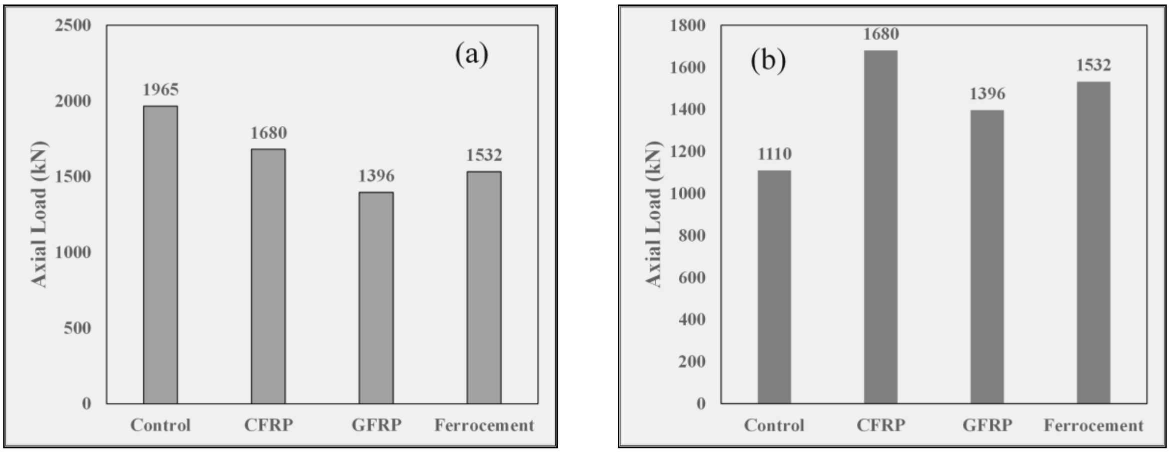

Figure 14. Comparison between repaired and control samples, (a) Non-heated and Non-repaired, (b) Heated and Non-repaired.

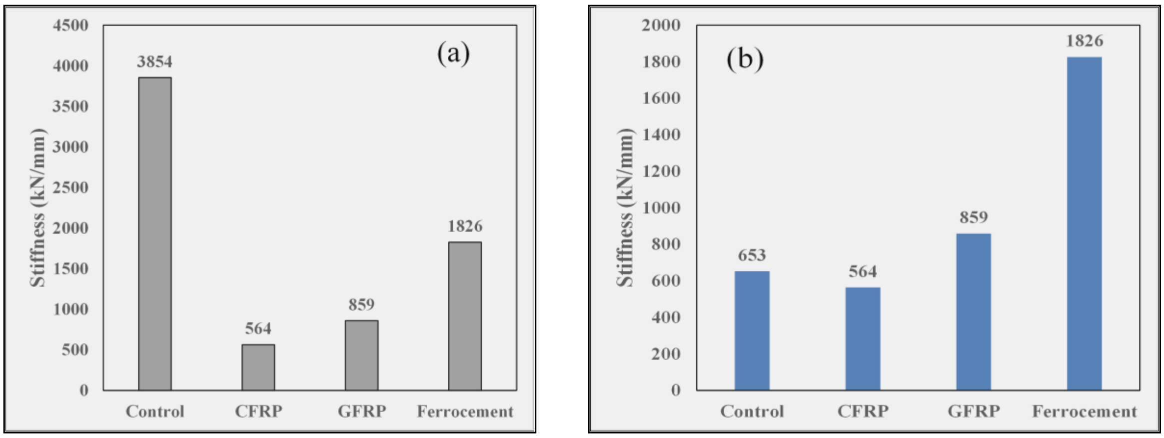

Figure 15. Comparison between repaired and control samples, (a) Non-heated and Non-repaired, (b) Heated and Non-repaired.

CONCLUSIONS

The paper's main goal was to review different materials used by different researchers in the case of fire-damaged concrete and their performance evaluated. After the review of the literature, the following points are concluded:

a) Ultra-high-Performance-fiber reinforced concrete has a good bond and tensile strengths, which gives high performance for repairing flexural members. Furthermore, the test on using it for repair should be investigated.

b) Using CFRP could not restore stiffness. However, the toughness increased.
c) Ferrocement is cost-effective, and it is better in restoring stiffness and toughness for the repaired structure compared to CFRP.
d) Using shotcrete is very effective since there is no need to use formwork.
e) The heat used in the research does not represent actual fire well. Therefore, it is recommended to use actual fire to damage the concrete sample.
f) Exposure of different concrete strengths to fire should be investigated to know the effect of fire on the concrete strength reduction.

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