AN EVALUATION OF REPAIR MATERIALS USED FOR REINFORCED CONCRETE STRUCTURES DAMAGED BY FIRE: A REVIEW

Abstract

Fire incidents pose challenges to reinforced concrete (RC) structures, but their low heat conductivity generally allows for repair rather than complete demolition and reconstruction. When exposed to temperatures above 500 °C, the inherent mechanics of the RC structure, encompassing, strength under compression, rigidity, and strength under tension deteriorate, leading to reduced residual strength. However, visible damage may not always be apparent. To address this issue a wide range of materials including carbon fiber-reinforced polymer, glass fiber reinforced polymer, conventional strength concrete, fiber reinforced concrete, ferrocement, epoxy resin mortar, and high performance concrete can be employed.Picking the suitable mending substance that harmonizes with the underlying surface is pivotal to achieve a triumphant restoration.This review assesses the existing repair materials and their performance factors. Notably, ultra high performance fiberreinforced concrete (UHPFRC) holds significant promise for rehabilitating fire damaged RC structures, although additional research is needed to fully explore its potential. In conclusion, RC structures can be effectively repaired following fire damage, provided that the right repair materials are selected and applied, potentially saving them from costly reconstruction.

Keywords: Fire Incidents, Reinforced Concrete Structures, Repair Materials, Mechanical Properties, Compressive Strength, Stiffness, Tensile Strength, Residual Strength, Visible Damage.

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I. INTRODUCTION

Reinforced concrete (RC) is known for its remarkable fire resistance attributed to its low heat conductivity, which effectively safeguards the structural integrity of its concrete core and internal reinforcing steel. According to EN1994 [1] and EN1993 [2], the heat conductivity of RC is approximately 1.5 W/mK, significantly lower than that of steel which is about 45 W/mK. Furthermore, as outlined in EN1992-1-2 [3], the heatconductivity of concrete diminishes as the nearby environment temperatures rise. Nonetheless, it's important to note that extended exposure to high temperatures can lead to a reduction in the mechanical strength of concrete and the properties of the embedded steel reinforcement bars. In a study it was revealed that there is potential to further elaborate on the compressive strength of concrete may decrease by up to 50% when subjected to temperatures of 600°C. When exposed to even higher temperatures, such as 800°C,the remaining compressive strengthplummets to only 20% of its original value[4].Notably, in normal-strength concrete, the declinein terms of tensile splitting strength at 600°C is even more pronounced compared to the decrease in compressive strength. Moreover, elevated temperatures can bring about changes in the concrete's pore arrangementresulting in heightened permeability, and reduced overall durability. For instance, after being exposed to 600°C, the cumulative pore volume in normal-strength concrete doubles. Temperatures exceeding 600°C can trigger severe dehydration of the C-S-H gel and further coarsening of the pore structure, both contributing to a notable loss of strength in the concrete [4].instances of fires causing significant global structural damage in concrete structures are rare, most affected structures can be effectively restored. Consequently, the restoration and rehabilitation techniques applied to concrete structures that have been adversely affected by the effects of fire presents a practical and cost-efficient alternative when compared to the more drastic options of demolition [5,6]

II. ELEMENTS AND TECHNIQUES FOR STRUCTURAL REPAIR

Selecting the proper repair material is a crucial aspect of the restoration process, requiring careful consideration of factors such as compatibility with the existing base material, specifications, available technical resources, budgetary constraints, and specific project requirements [8]. In general, the materials used for repairs should closely approximate the original building material. In previous research, Normal Strength Concrete (NSC) was frequently used for restore fire damaged concrete elements [9]. Significantly evaluated the performance of Reinforced Concrete (R-C) columns repaired with cast in place Normal Concrete (N-C) following fire damage. However, there is a dearth of research on the effectiveness of NC as a fire-damaged structure restoration material. Shotcrete, a cementitious material, has been frequently employed by engineers for the purpose of restore fire damaged RC components [8]. Shotcrete, unlike NC, eliminates the need for formwork, resulting in a reduction in construction time and the need for concrete pouring and consolidation. It has rapid setting times and displays high mechanical properties at an early stage, making it a popular choice for a variety of applications, including rapid restorations, slope reinforcement, and subterranean structures [10]. In various structural contexts, Prugar et al. [11] and Gosain et al. [8] repaired fire-damaged RC elements with shotcrete. Epoxy resin mortar constitutes another option in this context commercially available cementitious option for repairing damaged RC members. Yaqub and Bailey [6] repaired extensively fire-damaged RC columns with epoxy resin mortar. However, data regarding the effectiveness of shotcrete and epoxy resin in repairing fire-damaged structures remains limited. Researchers have utilized Ferro-cement, a composite composed of wire perforations and mortar, to restore fire-damaged RC structures. [12-13] Ferrocement is a cost-effective option for repairing dwelling structures in developing nations, despite its labor-intensive nature. Its minimal craftsmanship requirements and use of locally available raw materials make it a viable option. Despite its age, the use of ferrocement to repair fire-damaged RC elements has been scarcely documented. Its adaptability in encasing structural members with varying cross-sections suggests structural repair potential. Nonetheless, the process of installing and interconnecting rods and meshes can be arduous and time-intensive, which renders it less appropriate for application in commercial edifices and bridges. This is primarily due to the inherent limitations imposed by both time and cost factors. Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP), both of which are available in plate or sheet form, are prominent options for repairing defective RC structures [5, 6,15,19]. These materials feature easy application, a high strength-to-weight ratio, exceptional mechanical strength, and corrosion and chemical attack resistance. In addition, their low density minimizes the additional burden on the repaired structure and makes their application without the use of heavy machinery more convenient. As shown in Table 1, CFRP and GFRP exhibit substantially greater tensile strength than steel reinforcements in RC. Yaqub and Bailey [5] demonstrated that FRP sheets provide more effective confinement than square columns when repairing fire damaged circular cross section RC columns.Steelfiber-Reinforced Concrete (SFRC), which incorporates steel fibers into the concrete composition, is an appropriate option for repairing fire damaged RC members. It transcends the concrete's inherent low tensile strength and brittle failure. Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) is a cementitious material with increased compressive and tensile strength and enhanced ductility compared to Normal Concrete (NC). UHPFRC is produced by combining thin steel fibers, aggregates, and water-reducing agents with a low ratio of water to cement. In comparison to conventional or high-performance concrete (HPC), it is denser and has less porosity, resulting in increased durability. UHPFRC's strain-hardening properties prevent the formation of shrinkage fractures, thereby enhancing its suitability for structural repair. In addition, the watertight nature of UHPFRC provides corrosion protection for embedded steel rods [24].

Table 1: Comparing Properties of Concrete, CFRP, and GFRP[5-6,15-19]

Material	Concrete	Steel	CFRP	GFRP
Tensile Elastic Modulus (GPa)	25	180	165-236	75
Tensile Strength (MPa)	3.5-5.8	495	2750-4050	1517-2300
Density (Kg/m^3)	2240-2400	7850	1500	1800

The decision-making process involved in choosing the most suitable option of repair method is contingent upon the nature of the fire-damaged RC member. In instances involving flexural members like slabs, beams, the repair material can be selectively applied to either the undersurface or the tensile face, or alternatively to both surfaces. Some researchers have even explored the viability of applying repair material to the compressive side (upper surface); however, the resultant impact has been deemed negligible [25]. Conversely, in the context of compressive members such as columns, the widely adopted technique is jacketing, irrespective of the specific repair material in use. Jacketing entails enveloping the compromised column with the repair material to augment its strength and structural integrity. This approach has demonstrated its efficacy in reinstating the load-bearing capacity and overall structural performance of fire-affected columns.

III. FACTORS INFLUENCING REPAIR PERFORMANCE OF MATERIALS

A number of factors influence the efficacy of repair materials. First and foremost, the extent of injury in post-heated RC members is crucial. Yaqub [5] identified two categories of damage in RC columns heated to 500 degrees Celsius: cracks with and without significant spalling. Columns with substantial spalling that were repaired with epoxy resin and GFRP sheet sheathing had their load capacity increased by up to 110%. On the other hand, fire-affected reinforced concrete columns exhibiting minimal spalling that were repaired solely with GFRP demonstrated an increase in capacity up to 129% of the original.

The bond strength between the repair material and the original material is another crucial factor influencing the efficacy of repair materials [26, 27]. In general, concrete-based restorations exhibit strong adhesion to aged concrete, whereas the bond strength with materials such as epoxy requires consideration. Due to epoxy degradation in hot climates, FRP-repaired concrete beams exposed to wet/dry conditions performed inadequately, according to Gomez [19]. However, UHPFRC and ferrocement exhibit reliable bond strength with fire-damaged concrete, with no issues of debonding. Surface treatment and substrate condition have an effect on the bond strength between cementitious restoration material and fire-damaged concrete substrate. Sandblasting is an effective technique for removing stray particles, which strengthens the bond between the repair material and substrate. Also suggested is pre-wetting the substrate surface prior to repair. Increased fire temperatures diminish bond strength. The adhesive potency between cast in place UHPFRC and fire-damaged concrete requires further investigation. Crucial to reinforcing fire damaged RC members, particularly columns, is the geometry of the cross-section. Compared to square cross-sections, Bailey [5] determined that circular cross-sections enclosed with FRP increase axial strength and ductility. Circular sections with FRP jackets confine concrete more effectively than square sections, which can result in inadequate confinement and increased tension at corners. The type of structural member being repaired, whether flexural or compression, influences the efficacy of repair materials such as FRP. FRP can improve the ductility of fire-damaged RC columns, but it may not completely restore their rigidity. FRP increases stiffness but not ductility in RC slabs. Understanding the behavior of FRP in reinforcing structural components subjected to deformation and compression requires additional study. Curing techniques have a positive effect on cementitious restorations. Curing fire-damaged concrete prior to repair improves its mechanical properties, including compressive strength and rigidity. Water curing substantially restores compressive strength and modulus elasticity; for instance, water curing enhanced the rigidity of fire damaged RC slabs by 56%. Therefore, it is advised to water cure fire-damaged substrates prior to applying restoration materials, after removing loose substances.

IV. FINDINGS OF PREVIOUS WORKS

In evaluating the efficacy of restoration materials, the ability to improve the original characteristics of robustness, rigidity, and malleability in fire-damaged RC members or structural systems is a common factor. Studies demonstrate that Fiber Reinforced Polymers (FRP) can significantly improve tensile strength, pliability, and energy absorption compared to their original levels [5, 6, 12, 15, 33]. Nevertheless, owing to different properties than concrete, FRP may not improve elastic stiffness. Efforts to augment column rigidity or FRP confinement may have a negative effect on column ductility [15]. Using two layers of Carbon Fiber-Reinforced Polymer (CFRP) restored the rigidity of fire-damaged RC beams by up to 160%, but fragility resulted. Ferrocement increases rigidity, but not entirely due to the increased surface area caused by jacketing. Combining FRP with ferrocement or Steel fiber-Reinforced Concrete (SFRC) appears to be an effective strategy. Ductility is crucial when assessing efficacy under extreme loads [12]. Shotcrete is preferred for repairs due to the absence of formwork. Shotcrete has been used effectively in research [8, 11], but rapid placement pressure increases density and the risk of spalling under fire. Ultra High Performance Fiber Reinforced Concrete UHPFRC effectively repairs fire-damaged RC beams and columns, but there are concerns regarding spalling and axial strength reduction. UHPFRC is more expensive owing to its higher cement content. Determine the optimal UHPFRC thickness for capacity restoration. The effect of fiber type on the tensile properties of UHPFRC is controversial. Assessing UHPFRC's efficacy in enhancing the capability of impaired RC members requires systematic research.

Table 2: Width of UHPFRC Layer Employed in Reinforcement

Study	**Explored UHPFRC Restoration for Structural Member**	**Thickness (mm)**	**%**
Lampropoulusetal[25]	Beam (preexisting)	50	300
Leonardietal[7]	Beamandcolumn	40	300
Martinolaetal,[42]	Beam(with inadequate compressive strength and under-designed reinforcement ratio)	40	200
Farhatetal[28]	Beam(insufficiently designed for flexural strength)	16	145

The impact of the cross-sectional shape on the efficacy of repair materials has been highlighted by both Bailey [5] and the present study. Consequently, it is essential for the purpose of ascertaining the efficacy of UHPFRC in rehabilitating RC members with different geometries or cross sections. Currently, there is a lack of extensive investigation on this aspect in the available literature. For example, only Leonardi et al. [7] exist. Analyzed numerically the possibility of UHPFRC for repairing fire-damaged square RC columns. More experiments are required to confirm the efficacy of UHPFRC in repairing RC members with varied geometries.

Understanding how UHPFRC behaves in various types of RC members will shed light on its suitability for extensive use in the repair and rehabilitation of fire-damaged structures. By investigating various geometries, such as circular, rectangular, and irregular cross sections, researchers can obtain a thorough understanding of UHPFRC's capabilities and limitations in addressing various types of fire-induced damages. Such research would considerably advance the field of repair materials for fire-damaged RC structures and aid engineers in making well-informed decisions regarding the best repair strategies. Therefore, future research should prioritize conducting exhaustive experiments to evaluate UHPFRC's effectiveness in restoring RC members with varying structural configurations [29-42].

Table 3: UHPFRC Tensile Strength and Impact on Load Carrying Capacity of Current Reinforced Concrete Beams [25]

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

V. CONCLUSIONS

Choosing suitable materials used to restore ensuring the significance of fire damaged RC elements for successful rehabilitation Repair materials need to match the damaged concrete and reinstateinitial strength. This study reviewed materials like CFRP, GFRP, FRC, ferrocement, epoxy resin mortar, and UHPFRC for fire-damaged concrete repair. Conclusions drawn from the study include:

1. Engineers prefer shotcrete due to its advantages, but its performance for the restoration of fire-affected RC needs more investigation.
2. Prior research showed promise in using CFRP and GFRP for restoring load-bearing capability and malleability in fire-damaged RC, though stiffness improvement may be limited.
3. FRC and ferrocement enhance stiffness, but restoring load capacity and ductility might be challenging.
4. Epoxy resin bonds well but may not suffice to enhance overall capacity in fire-damaged RC.

UHPFRC's durability, mechanical prowess, and ease of use position it as a promising option for fire damaged RC repair. Study explored UHPFRC's potential, but further experiments are needed to elucidate fire behavior for NSC and UHPFRC, establishing their real performance. Parameters like fiber content, UHPFRC thickness, and member geometry need thorough evaluation to grasp UHPFRC's potential as a fire-damaged RC repair material. Material selection, especially UHPFRC, can significantly aid successful rehabilitation. Studying various materials and their characteristics will inform decisions, ensuring structural safety. Prioritizing experimental investigations is key to fully understanding UHPFRC's capabilities and limitations as a fire-damaged RC repair material.

REFERENCES

[1] European Committee for Standardization. "EN1994-1-2." (2005).
[2] European Committee for Standardization. "EN1993-1-2." (2005).
[3] European Committee for Standardization. "EN1992-1-2." (2004).
[4] Chan, Y. N., Peng, G. F., & Anson, M. "Cem. Concr. Comp. 21. 23 (1999)."
[5] Yaqub, M., & Bailey, C. G. "Constr. Build. Mater. 25. 359 (2011a)."
[6] Yaqub, M., & Bailey, C. G. "Composite Structures. 93. 1103 (2011b)."
[7] Leonardi, A., Meda, A., & Rinaldi, Z. "Strain. 47. 28-35 (2011)."
[8] Gosain, N. K., Drexler, R. F., &Chouduri, D. "Struct. Eng. Mag. Struct. Forensic. 18 (2008)."

[9] Lin, C., Chen, S., & Yang, C. "ACI Struct Journal. 92. 406 (1995)."
[10] Xiang, K., & Wang, G. H. "Procedia Engineering. 52. 446 (2013)."
[11] Prugar, J. F., Osowski, S. M., & Brighton, J. "Proceeding of 4th Congress on Forensic Engineering (American Society of Civil Engineering, USA, 2006) pp. 502-515."
[12] Yaqub, M., Bailey, C. G., Nedwell, P., Khan, Q. U. Z., &Javed, I. "Composites: Part B. 44. 200 (2013)."
[13] Haddad, R. H., &Shannag, M. J. "Mater and Structr. 41. 287 (2008)."
[14] Naaman, A. E. "Ferrocement and Laminated Cementitious Composites." Techno Press 3000, Ann Arbor, 2000.
[15] Hannan, A., &Jawarneh, M. "Mater Structr. 50. 95 (2017)."
[16] Al-Rousin, R. Z., Haddad, R. H., &Swesi, A. O. "Composites: Part B. 70. 20 (2015)."
[17] Xiang, K., & Wang, G. H. "Procedia Engineering. 52. 446-452 (2013)."
[18] Brisby, L. A., Chen, J. F., Li, S. Q., Stratford, T. J., Cueva, N., &Crossling, K. "Engr. Structr. 33. 3381 (2011)."
[19] Toutanji, H. A., & Gómez, W. "Cement and Concrete Composites. 19. 351 (1997)."
[20] Haddad, R. H., Al-Mekhlafy, N., &Ashteyat, A. M. "Constr. Build. Mater. 25. 1213 (2011)."
[21] deLarrard, F., &Sedran, T. "Cement and Concrete Research. 24. 997-1009(1994)."
[22] Naaman, A. E., & Reinhardt, H. W. "Setting the stage: towardsperformance-based classification of FRC composites." In Proceedings of 4th RILEM symposium on high-performance fiber-reinforced cement, composites (HPFRCC4), (2003) pp. 1-4.
[23] Charon, J. P., Denarié, E., &Brühwiller, E. "Mater. Structr. 40. 269 (2007)."
[24] Martin-Sanz, H., Chatzi, E., &Denarie, E. "The use of ultra-high-performance fiber-reinforced cement-based composites in the rehabilitation project: A review." In 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures. Framcos-9 conference proceeding, edited by V. Souma et al. (University of California, Berkeley, USA, 2016) pp. 1-12.
[25] Lampropoulus, A. P., Paschalis, S. A., Tsioulou, O. T., &Dritsos, S. E. "Engineering Structures. 106. 370-384 (2016)."
[26] Gorst, N. J. S., & Clark, L. A. "Cem. Concr. Compos. 25, 1089 (2003)."
[27] N. K. Baharuddin, F. M. Nazri, R Putra Jaya, B. H. Abu Bakar. World Journal of Engineering. 13(5). 461(2016)
[28] E. Denarie, “Recommendation for tailoring of UHPFRC recipes for rehabilitation,” ARCHES Report, Lausanne, 2009.
[29] M.Z.A. MohdZahid and K. Muhammad, “The assessment of bond strength between heat damaged concrete and high strength fiber reinforced concrete” in AIP Conf. Proc. 1885, 020117- 020117-6; doi: 10.1063/1.5002311
[30] A Hanan, R. Haddad, S. Afram, M. Abdel-Halim, Materials and Structures. 46. 1843-1860 (2013)
[31] D. Wang, C. Shi, Z. Wu, J. Xiao, Z. Huang, Z. Fang. Construction and Building Materials. 96. 368-377 (2015)
[32] H. Abdullah, M.Z.A. MohdZahid, B.H. Abu Bakar, F. M. Nazri, and A. Ayob, Appl. Mech. & Mater. 802, 283 (2015)
[33] C. Kahanji, F. Ali, A. Nadjai, Journal of Structural Fire Engineering. 7(4). 328-348(2016)
[34] ISO 834-1. Fire resistance test – element of building construction. Switzerland. (1999)
[35] Y. A. Al Salloum, T. H. Al Musallam, H. M. Elsanadedy, R. A. Iqbal. Constr. Building Materials.115. 345-361(2016)
[36] V. Kodur. ISRN Civil Engineering. 1-15(2014)
[37] O. Arioz. Fire Safety Journal. 42. 516-522(2007)
[38] U. Shneider. Fire Safety Journal. 13. 55-68(1988)
[39] M. N. Fardis. Innovative materials and techniques in concrete construction: ACES Workshop. Springer Dordrecht Heidelberg London New York: University of Patras; 2012
[40] J. Liu, F. Han, G. Cui, Q. Zhang, J. Lv, L. Zhang, Z. Yang. Construction and Building Materials. 121. 310-318 (2016)
[41] K. Wille, S. El-Tawil, A. E. Naaman. Cement & Concrete Composites. 48. 53-66 (2014)
[42] G. Martinola, A. Meda, G. A. Plizzari, Z. Rinaldi. Cement & Concrete Composites. 32. 731- 739(2010).
[43] "Review of RepairMaterials for Fire-Damaged Reinforced Concrete Structures", IOP Conference Series:Materials Science and Engineering, K Muhamad.(2018)