BEHAVIOUR OF CONCRETE AT HIGH TEMPERATURE: A REVIEW

Saqib Khalid[1], Muhammad Saad Hassan[2], Wasif Ali[3], Mehran Sudheer*[4] and Majid Ali[5]

[1] *BS Student, Capital University of Science and Technology, Pakistan, e-mail: saqibskkhalid@gmail.com*
[2] *BS Student, Capital University of Science and Technology, Pakistan, e-mail: saadrajapeace@gmail.com*
[3] *BS Student, Capital University of Science and Technology, Pakistan, e-mail: h.wasifali@gmail.com*
[4] *Lecturer, Capital University of Science and Technology, Pakistan, e-mail: mehran.sudheer@cust.edu.pk*
[5] *Professor, Capital University of Science and Technology, Pakistan, e-mail: majid.ali@cust.edu.pk*

*** Corresponding Author**

ABSTRACT

Concrete is widely used in the infrastructure development such as buildings, bridges, industrial structures and other building structures etc. Fire is a huge threat that can endanger people's lives, environment, and infrastructure. Buildings contain a variety of direct and indirect fire hazards, and the early stages of a fire pose a significant risk to life, structural damage, loss of property, and the environment. The nature of the fire, the fire types, and the type of structure all influence structural concrete failure in a fire. Although concrete is a nonflammable material, when exposed to high temperatures, its physical, chemical, and mechanical properties deteriorate. Concrete and heat have a complicated relationship, which depends on the chemical structure of concrete and the intense heat conditions commonly observed in fire. This paper emphasizes on significant advancements in fire research for instance fire types, magnitudes, and their impact. Concrete behaviour during fire, immediate after fire and their residual strength were reviwed to give a clear picture of concrete at high temperature. In addition, different methods for recovering concrete strength were also reviewed.

Keywords: *Concrete, High temperature, Mechanical properties, Structure.*

1. INTRODUCTION

Concrete is frequently utilised in the construction of infrastructure like as buildings, bridges, cooling towers, chimneys, industrial structures, and other numerical constructions. One of the most devastating unintentional loads to which a structure may be subjected during its lifespan is fire. The amount of damage produced will be determined mostly by the severity and duration of the event. The temperature and duration of fire affect the physical qualities of concrete and reinforcing steel. Normally, rehabilitating fire-damaged structures is chosen over dismantling and rebuilding (Parthasarathy et al., 2014). Concrete-based structures, by their very nature, perform very well in fires. However concrete, on the other hand, is a fundamentally complex material whose characteristics can drastically change when subjected to high temperatures.

The main impacts of fire on concrete are the loss of compressive strength and the formation of cracks known as spalling effect (Fletcher et al., 2007). Concrete under the different compartments of fires having different magnitude have resulted in spalling effect and decrease in residual compressive strength of concrete (Helene et al., 2019). When a fire exposes concrete to intense heat, the temperature shock to the material can cause considerable damage. Concrete, like most other materials, expands as it is heated. When exposed to high temperatures, the outside layers expand more faster than the core regions. This "differential expansion" is not easily absorbed by the concrete, causing the layers to split and eventually break apart. When a fire is extinguished by hose streams or automatic sprinkler systems, the same process might occur in reverse. In this instance, as the hot concrete cools rapidly, the outer layer may shrink at a different rate and separate (Annerel & Taerwe 2016).

In most fires, the severity and intensity of the fire impair the concrete structure's stiffness and strength to the level where, but instead destroying and rebuilding the fire-damaged concrete structures, repair is the most economically and technically practical option. The ability to restore the strength and stiffness of fire-damaged materials utilising various composite confining techniques has demonstrated that strength of concrete, deformation capacity, load bearing capacity, and energy disposal capability are all improved (Usman et al., 2021). This paper presents an overview of the many types of fires, their impact and severity, including the behaviour of concrete during and after a fire and its residual strength. Furthermore, a review of viable strategies for regaining concrete strength is addressed.

2. CONCRETE BEHAVIOUR UNDER HIGH TEMPARTAURE

2.1 Fire types, magnitudes, and their impact

"Fire is caused by the combustion process, which generates light and heat." Considering significant advancements in fire research, Seito et al. (2008) asserts that there is still no worldwide agreement on how to define fire due to a lack of clarity in the definitions of main global standards in use. A hypothesis known as the Fire Triangle was initially developed, according to Seito et al. (2008), and it comprised of three essential elements: fuel, oxidizer (oxygen), and heat. If any of these components were removed from the triangle, the fire would be quenched instantaneously, as per this theory. A fire is started, maintained, and spread using the element of heat. Oxidizer (oxygen) is present in the air we consume and is required for combustion. Fuel, which can be solid, liquid, or gas, is the ingredient that spreads fire. Because of the chain reaction, the burning process is self-sustaining. The heat emitted by the flames reaches the fuel, which is divided up into smaller particles that mix with oxygen and burn, radiating heat back into the fuel and creating a continuous (self-sustaining) cycle. Fire usually begins in tiny amounts, and its spread is determined by the initial ignited object, the fire performance characteristics of nearby materials, and its dispersion in the environment. Fire has various stages:

- Ignition happens when a long-term chemical process involving oxygen, fuel, and heat occurs. At this time, you can use a fire extinguisher to put out the flames.
- Because the first flame acts as a heat source, more fuel ignites. Convection and radiation ignite another surface. The fire expands, and a cloud of smoke rises to the ceiling. Hot gases that concentrate near the ceiling transmit heat, bringing various combustible together in a room closer to ignition temperature at the same time.
- Completely built: The flame had escalated to most, in case none, of the available fuel; temperatures have reached their highest point, causing thermal effect. Oxygen is quickly depleted.
- Burnout (decay): The fire consumes all available fuel, and the temperature rises.

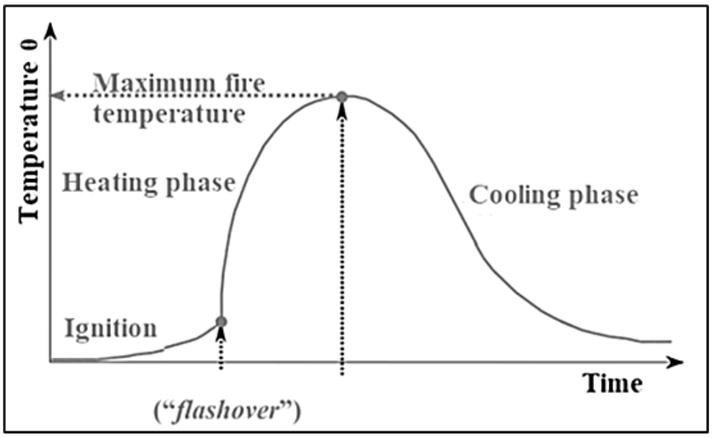

Figure 1: Various phases of fire (Costa & Silva, 2003)

Understanding differences between different types of fires can save lives. Depending on the agent that ignites the fire, it can be categorized into five categories: Type A, Type B, Type C, Type D, and Type K (Asyraf et al., 2020). are the different types of classes. Different flammable materials are involved in each type of fire.

- Type A: Normal flammable substances for instance timber, fabric, paper, rubber, and many synthetic materials. They burn with coal leaving ashes. Extinguish the fire by cooling the fuel to a temperature lower than the point at which it starts to burn. Fire quench additives such as water are effective.
- Type B: Flammable liquids (burn at room temperature) and flammable liquids (heat required to ignite). Petroleum grease, tar, oil, oil-based paints, solvents, lacquers, alcohol, and flammable gases. High fire risk: water may not go out. Create a barrier between fuel and oxygen, such as a layer of foam, to extinguish the fire.
- Type C: It contains energized electrical equipment, fuel that becomes A or B. Certain techniques and chemicals, most commonly carbon dioxide or dry chemicals, are required to extinguish a fire. Water is extremely dangerous to use since it conducts electricity.
- Type D: Metals that are flammable include magnesium, titanium, zirconium, sodium, lithium, and potassium. Most automobiles have a high concentration of such metals. Water may be split down into hydrogen and oxygen due to the extremely high flame temperature, which can speed up combustion and explosion. Extinguish the fire with a specific powder containing sodium chloride or other salts. Cleans dry sand as well.
- Type K: A fire in a cookware containing a flammable cooking medium (vegetable or animal fat).

When compared to the average fire, Origin structure fires have the largest number of fatalities, injuries, and monetary losses. Structure fires are often associated with buildings, which have a larger percentage

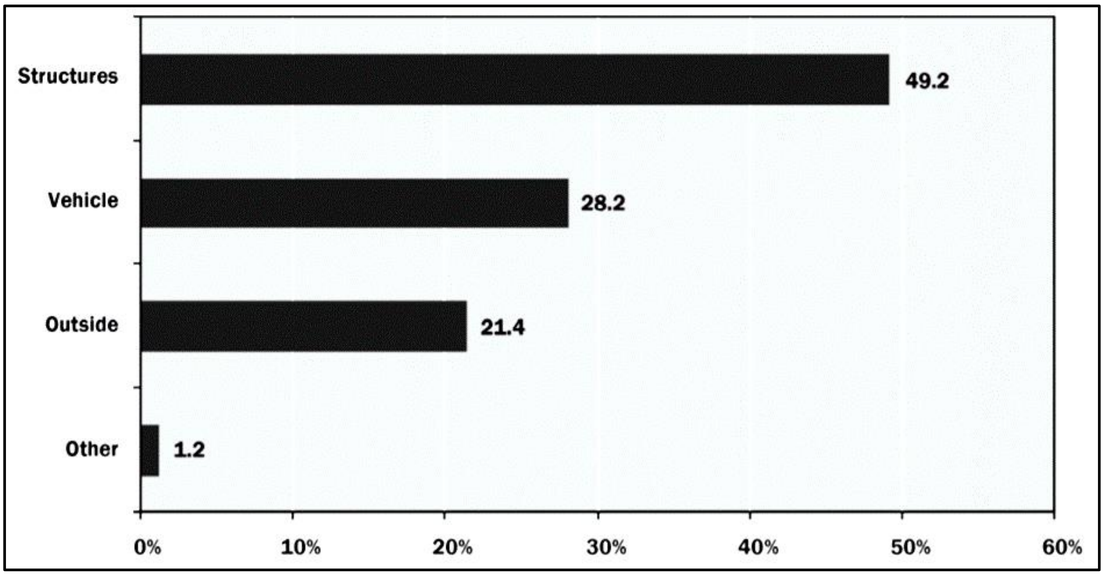

Figure 2: Source Fire Distribution by General Incident Type, 2004 (Topical Fire research series 2021)

of persons and property than other forms of fires. When compared to the average flame, origin fires have significantly larger incidence of injuries, fatalities, and monetary damage. Incendiary or suspicious, open flame, ember, or torch, and other heat, flame, or spark are the top three causes of source fires. Numerous vehicle fires, for example, are classified as incendiary or suspicious. Candles, matches, lighters, and cigarettes with open flames can start devastating fires. Fireworks or appliance and machinery malfunctions can cause fires caused by other heat, flame, or sparks. Following figure shows cause and distribution of fire source (Topical Fire research series 2021);

2.2 Concrete behaviour during fire, immediate after fire and their residual strength

Concrete and heat have a complicated relationship, depends on the chemical structure of concrete and the intense heat conditions commonly observed in fire. Concrete is not a homogenous material; it is a mixture of cemented gel, aggregates, and, in several situations, steel (or other) reinforcement. Each one of these elements responds differently to heat exposure, therefore the behaviour of the composite system under fire is difficult to characterize or model (Khoury G.A, 2000).

When concrete is subjected to heat, it goes through several physical and chemical transformations (Khoury G.A, 2000; Bazant et al., 1996; Wu Y, 2007). Some of them are reversible once the fire has been extinguished, while others are permanent and can cause considerable structural damage. Most porous concretes include a small quantity of liquid water. When the temperature goes over 100°C, the water vaporizes, allowing pressure to build up inside the concrete. Boiling temperatures in practice generally range from 100 to roughly 140°C due to pressure factors. Because when heat in the cement exceeds 400°C, the calcium hydroxide starts to dehydrate, releasing more vapour and reducing the material's physical strength significantly. Other alterations may occur in the aggregate at higher

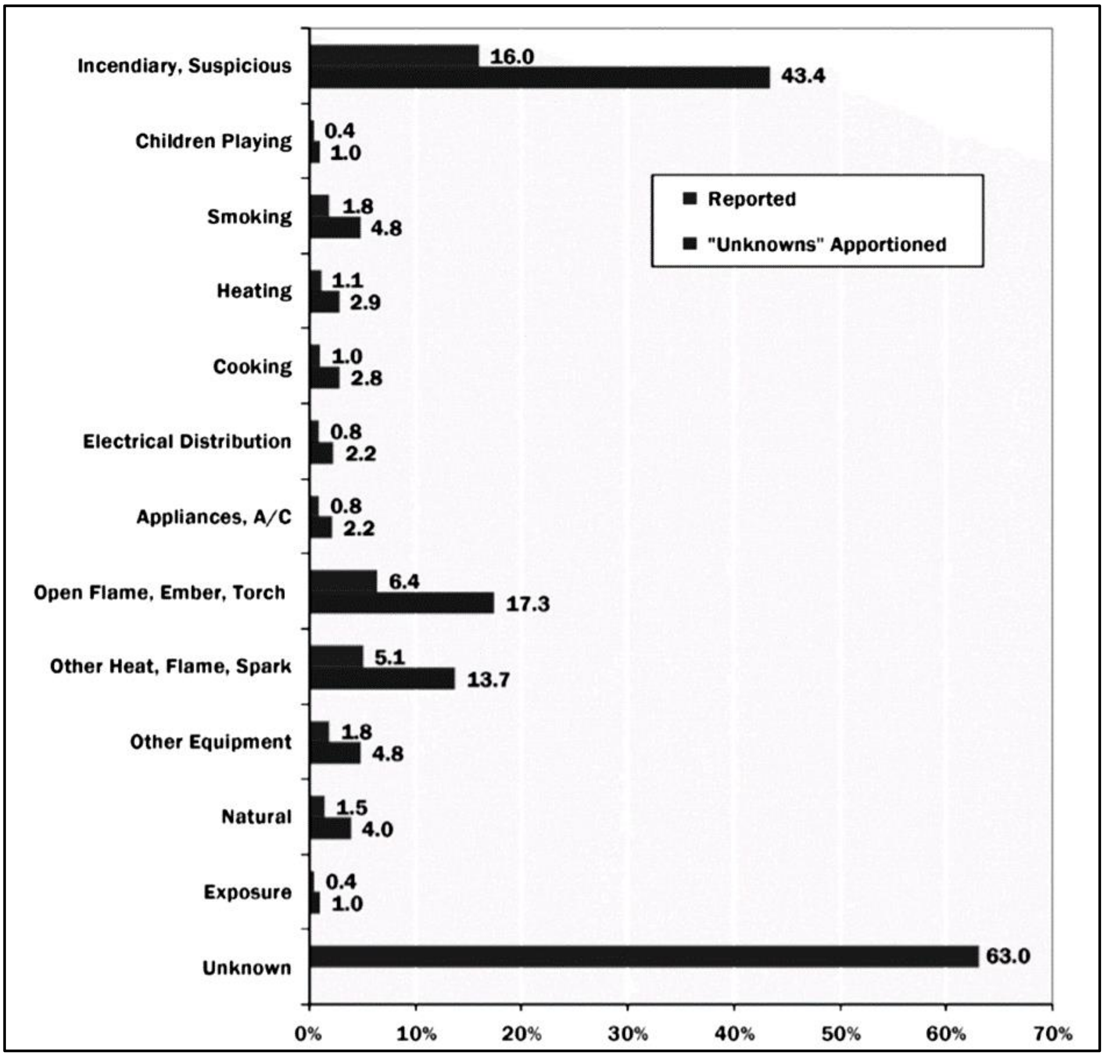

Figure 3: Source Fire Cause Distribution, 2004 (Topical Fire research series 2021)

temperatures. When these physical and chemical changes in concrete are coupled, the material's compressive strength is reduced. Explosive spalling (Fletcher et al., 2009; Tenchev & Purnell 2005) is one of the most complicated and poorly understood behavioural characteristics of concrete's reactivity to high temperatures or fire.

Figure 4: Example of explosive spalling occurred in high strength concrete column (Kodur et al., 2005).

Although it is commonly considered that this process only occurs at high temperatures, it has been recorded in the early stages of a fire and at temperatures as low as 200°C (Both et al., 1999; Schneider, 1988). Due to increased heating of the steel reinforcement, significant spalling can have a negative impact on the strength of reinforced concrete structures. In addition, the processes that cause cracking are thought to be comparable to those that cause spalling. Instead of, or in addition to, explosive spalling, thermal expansion, and dehydration of the concrete owing to heating may result in the creation of cracks in the concrete. These fractures could allow direct heating of the reinforcement bars, potentially leading to increased thermal stress and cracking. The fissures may enable paths for fire to spread across adjacent compartments in certain circumstances.

Changes in the structural qualities of concrete do not reverse themselves after a fire, unlike steel structures, which may sometimes be effectively restored to their former state by cooling. This is due to the cement's physical and chemical properties undergoing irreversible changes. Based on a post-fire evaluation of the state of the concrete surface, such alterations could be employed as indicators of maximum exposure temperatures (Placido, 1980). It's worth noting that, in some cases, even if there's no visible damage, a concrete structure might be significantly weakened after a fire. Residual strength of concrete on basis of previous shows us that Burning at 600°C results in a residual strength of less than 60%. This criterion indicates that concrete that has been fired or heated to temperatures exceeding 600°C cannot be reused. Concrete with a strength more than 35 MPa has a residual strength of more than 60% when burned at 400°C. These parameters suggest that concrete that has been fired or heated at temperatures less than 400°C can be reused, but only with certain modifications to the structure. Below the table shows physical effect of temperature on concrete. (From structure magazine 2008).

Table 1: Physical effect of temperature on concrete (From structure magazine 2008)

Temperature	Color change	Changes in physical temperature and Benchmark temperatures	Concrete condition
0 to 290°C	None	Unaffected	Unaffected
290 to 590°C	Pink to red	Surface cracking:300°C deep cracking 550°C,Poputs over chert or quartz aggregate .	Sound but strength significantly reduced
590 to 950°C	Whitish grey	Spalling, exposing not more than 25% of reinforcing bar surface 800°C, Powdered, light colored, dehydrated paste at 575°C	Weak and friable
950 + °C	Buff	Extensive spalling	Weak and friable

2.2.1 Concrete Behaviour during Fire

During fire the concrete mechanical property deterioration as temperature rises, caused by physical and chemical properties in the material during heating (Table 1); and volatile spalling, which results in material loss, section size reduction, and exposure of the reinforcing steel to excessive temperatures. As a result, the concrete member's separating/insulating, and load-bearing features may be jeopardised. The degradation of concrete's mechanical characteristics upon heating can be attributed to three material factors: physicochemical changes in the cement paste, physicochemical changes in the aggregate and thermal incompatibility between the aggregate and the cement paste. (Khoury G.A, 2000).

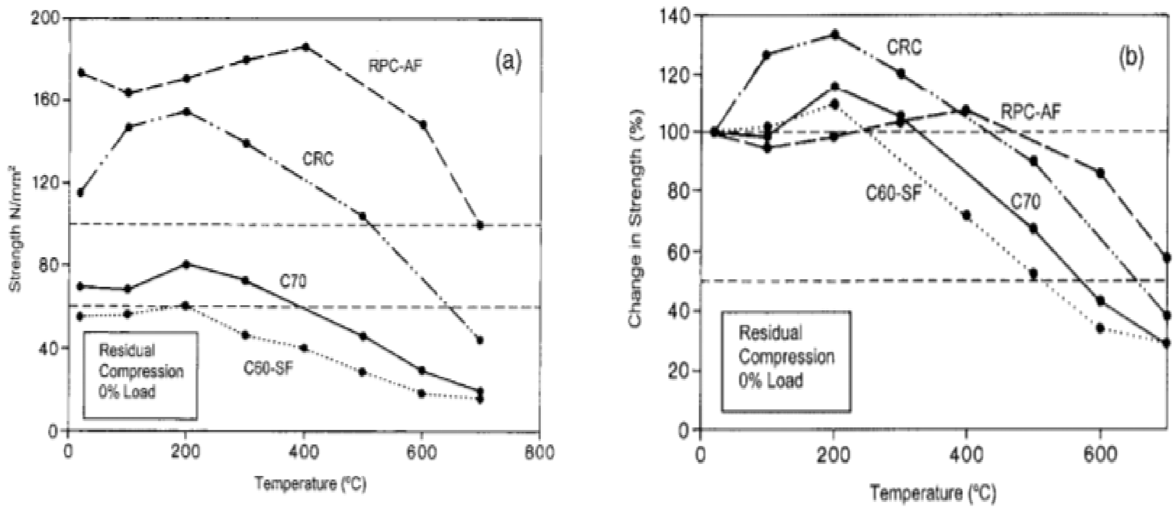

Figure 5: The impact of temperature on the residual compressive strength of two high-performance concretes (C60-SF, C70) and two ultra-high-performance concretes (CRC, RPC-AF) after heat cycling at 2°C min (a) Actual values; (b) initial strength percentage at 20°C. (Khoury G.A, 2000).

2.2.2 Concrete Influence Immediate after Fire

Heat has an influence on the structural and thermal properties of concrete and steel. When mechanical properties lose toughness and resistance, structural components are damaged. Thermal propagation causes heat exchange from the burn component to other structural components. Mechanical properties of concrete and reinforcing substances encompass a reduction in compression and tension, and a rise and fall in strain (Dwaikat & Kodur, 2009). Fire, particularly post-earthquake fires, poses a significant threat to human civilization. This is a once-in-a-lifetime event with far-reaching consequences. Concrete strength deterioration at extreme temps is caused by chemical-physical processes, and mechanical deterioration within the concrete matrix is one of the most important phenomena influencing a building's load-bearing capability under fire conditions. The experimental data was summarised as interactions among concrete, heat, and relative strength properties degradation. A range of indicators, including aggregate type, concrete porosity, and member size, as well as heating and loading duration, influence the reduction in strength of concrete at high temperatures (Chudzik et al., 2017). The thermal expansion of the strengthening bars caused a deterioration of concrete cover along the longitudinal borders in the support areas and local areas at the base of the major beams.

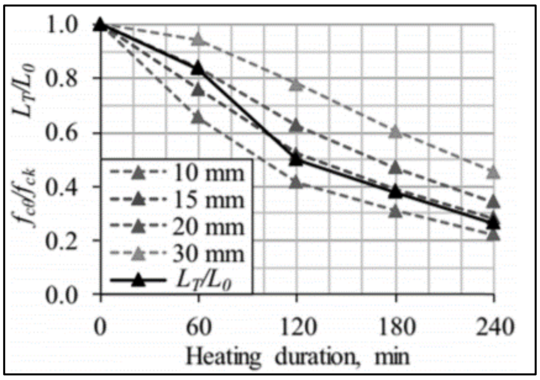

Figure 6: The compressive strength of concrete decreases at various cross-section depths as a function of heating time (Kowalski & Wróblewska, 2018).

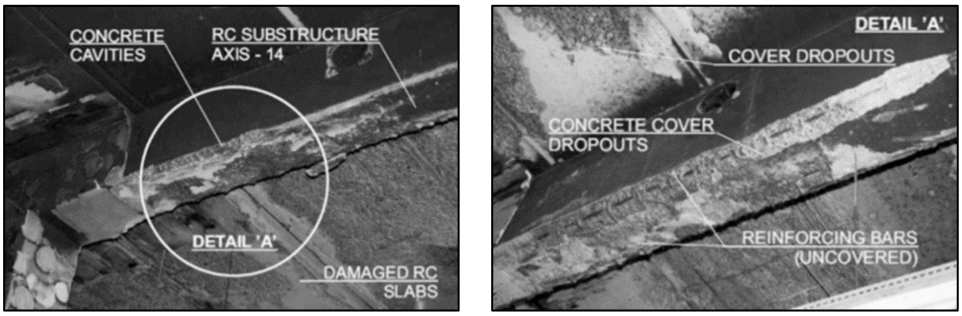

Figure 7: View of the cover reinforcement loss: left figure-Support region and right figure-Span region (Knyziak et al., 2019).

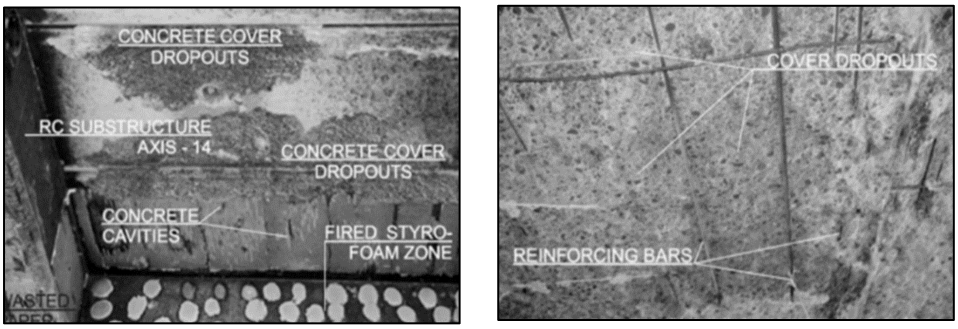

Figure 8: Detail floor slabs damage: left figure-Cover local defects and right figure- Peel-off concrete cover in reinforced bars region (Knyziak et al., 2019).

2.3 Methods for Recovering Concrete Strength

Many options for retrofitting a structure after a fire are available, but the most common ones are strengthening structural members with different types of composite confinement, fiber reinforced plastic, and replacing damaged concrete with shotcrete or in situ concrete placement. (Ankit & Dr. Deepa., 2016). The methods of rehabilitation are as follows:

1. Fiber reinforced polymer
2. Concrete jacketing
3. Steel jacketing
4. Different types of composite confinement.

1. Fiber-reinforced polymer is a fully synthetic compound consisting of a polymer matrix reinforced by fibers. FRP is a long-lasting material when properly handled. It is unlikely to oxidize, unlike steel, because it is non-corrosive. Because it will be easily moulded into shapes and can cover practically all construction geometry without using formwork, FRP material does not necessitate specialized labor. As a result, by utilizing waste fibres, it might be called a long-term mending strategy. (Bisby et al., 2011).
2. Concrete jacketing is a method for repairing structural members made of concrete. In a fire-damaged building, concrete jacketing could provide additional stability to structural parts that have been damaged. (Zhou & Wang., 2019).
3. Steel jacketing is a method of encasing a structural element in steel angle, channel, and bands to create confinement and boost the element's flexural durability. Steel is an environmentally friendly material because it does not deplete fossil fuels or waste a lot of energy in its production, as FRP does. As a result, it can be considered a sustainable repair method. (Zhou & Wang., 2019).
4. Different types of composite confinement: Composites confinements such as epoxy resin mortar injected steel wire mesh jointly confined with CFRP composite wrapping, CFRP composite wrapping system etc can be used for rehabilitation. (Usman et al., 2021).

FRP confinement's efficiency for fire-damaged concrete. Figure 5 plots the strength increase due to FRP wrapping, both as a percentage of the unconfined concrete strength (Fig. 5(a)) and as an absolute compressive strength increase (in MPa), over and above the unconfined compressive strength (Fig. 5(b)), with exposure temperature (again, solid lines show the average trends). For larger levels of damage, FRP confinement clearly leads in a proportionally greater improvement in compressive strength. However, as shown in Fig. 5(b), the average absolute compressive strength gain owing to FRP wrapping (in MPa) is very stable across all levels of thermal damage (or unconfined compressive strength). This shows that improving concrete strength is dependent on the underlying physical features (such as the internal friction angle) of the concrete mix, rather than the unconfined compressive strength, as reported by (Fam A & Mandal 2006).

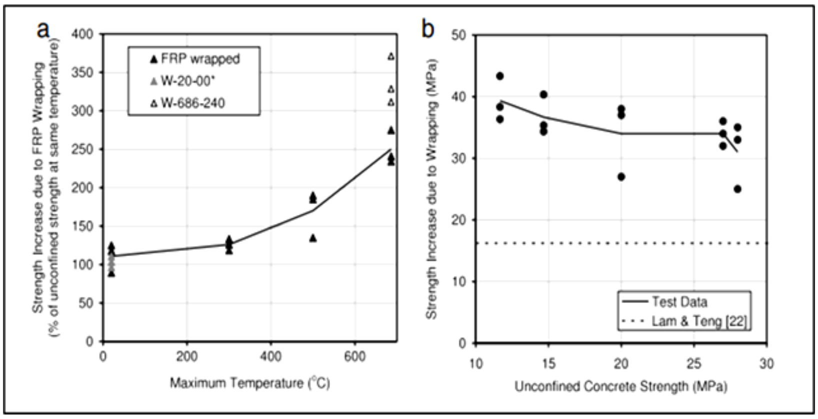

Figure 9: Effect of unconfined concrete strength on absolute strength gain caused by FRP wrapping (from Bisby et al., 2011)

Fiber-reinforcing polymer was used to repair fire-damaged concrete. Ultrahigh performance fiber-reinforced concrete (UHPFRC) is an excellent repair material due to its superior properties. UHPFRC's low permeability provides additional protection for the damaged substrate. UHPFRC's excellent performance makes it ideal for concrete rehabilitation, particularly for fire-damaged concrete. UHPFRC has a high bond strength to the substrate, indicating that it is a superior repair material (Baharuddin et al., 2016). Lin et al. (1995) Stated that mechanical behaviour of RC columns after they've been restored due to significant fire damage The gross cross-sectional area of the columns, longitudinal steel reinforcement yield strength, fire duration, and the placement of the applied concentrated load were the primary characteristics evaluated in this study. For undamaged, damaged unrepaired, and damaged repaired columns, load-curvature curves were plotted. The findings demonstrated that replacing the outer degraded concrete layers with a concrete of better strength and durability can restore full or even higher strength. The relevance of surface roughening and preparation was discovered to be critical in preventing premature failure of the restored columns due to spalling of the new concrete cover.

Zhou & Wang (2019) presented that the fire-damaged RC columns were repaired using the section enlargement method, steel wrapping strengthening, and externally bonded reinforcing (EBR) technique. The section enlargement approach, especially for compressed members, can significantly improve structural bearing capacity, stiffness, and stability. Despite its simplicity, the building's clearance is lowered, which has an impact on its eventual use. The advantages of NSM FRP jacketing over steel jacketing and concrete enlargements include simplicity of handling, light weight, anti-corrosion, and a high strength/stiffness-to-weight ratio. Meanwhile, when compared to EBR (external bonded reinforcement) jacketing, the benefits of NSM FRP jacketing are more apparent, such as superior FRP anchoring and ductile performance. Because of the confinement effects produced by the FRP jacketing, the concrete was subjected to three-directional compression, greatly increasing the ultimate strength of the columns. Moreover, the use of the CFRP composite prepreg system boosted the compressive strength, load bearing strength, distortion strength, flexibility, and energy dissipation strength of both preserved and fire-damaged buildings.

From the studies it has been concluded that all structures that have been damaged by fire should be assessed in a methodical manner to identify the degree of the repairs that are required. By monitoring the collateral damage, the intensity and duration of the fire can be calculated. Evaluations, when combined with an engineering study, allow for the development and installation of effective and cost-effective repair details as needed. Assessment aids in the reduction of construction costs and the avoidance of needless projects.

3. CONCLUSION AND RECOMMENDATION

In this paper, the behaviour of concrete under high temperature was presented. The paper focused on change in residual strength and other properties when exposed to high temperature. The conclusions of present study are listed as follows:

- Different kinds of fire have various effects. Primary structure fires have the highest number of deaths, injury, and financial loss rates when compared to other types of fires. Building fires typically involve a greater proportion of people and property than other types of fires. In comparison with the ordinary fire, source fires cause far more injuries, deaths, and financial loss.

- The nature of the fire, the fire types, the loading systems, and the type of structure all influence structural concrete failure in a fire. Failure can occur due to bending or tensile strength loss, yield strength loss, shearing or rotational strength loss, compressive strength loss, or concrete cracking. Concrete has experienced spalling and a reduction in residual compressive strength because of different compartments of flames of various magnitudes.

- In most fires, the intensity and tenure of the fire impair the concrete building's strength and stiffness to the point where, rather than destroying and reconstructing the fire-damaged concrete buildings, repairing is the most financially and technically practical option. The ability to restore the strength and rigidity of fire-damaged materials utilizing different hybrid confinement strategies has demonstrated that strength of concrete, deformation capability, load bearing capacity, and energy disposal capacity can bel improved.

As a further research work, it is suggested to develop more efficient rehabilitation techniques with extreme/variable conditions that enable fire-damaged structures. On other hand sustainable techniques should be approached for strength recovery of fire-damaged concrete.

REFERENCES

Srinivasan, P., Cinitha, A., Mohan, V., & Iyer, N. (2014). Evaluation of fire-damaged concrete structures with a case study.

Fletcher, I., Welch, S., Torero, J., Carvel, R., & Usmani, A. (2007). Behavior of concrete structures in fire. *Thermal Science*, 11(2), 37–52.

Helene, P., Britez, C., & Carvalho, M. (2019). Ações e efeitos deletérios do fogo em estruturas de concreto. Uma breve revisão. Revista alconpat, 10(1), 1–21.

Annerel, E., & Taerwe, L. (2016). Combined Effects on Residual Strength of a High Performance Concrete Exposed to Fire. *Key Engineering Materials*, 711, 465–47.

Usman, M., Yaqub, M., Auzair, M., Khaliq, W., Noman, M., & Afaq, A. (2021). Restorability of strength and stiffness of fire damaged concrete using various composite confinement techniques. *Construction and Building Materials*, 272, 121984.

Khoury, G. A. (2000). Effect of fire on concrete and concrete structures. *Progress in Structural Engineering and Materials*, 2(4), 429–447.

Bažant, Z. P., Kaplan, M. F., & Bazant, Z. P. (1996). Concrete at High Temperatures: Material Properties and Mathematical Models. www.scholars.northwestern.edu.

Wu, Y. (2007). Fire Safety Journal, 42(3), 243-244. https://doi.org/10.1016/j.firesaf.2006.11.003

Tenchev, R., & Purnell, P. (2005). An application of a damage constitutive model to concrete at high temperature and prediction of spalling. *International Journal of Solids and Structures*, 42(26), 6550–6565.

Schneider, U. (1988). Concrete at high temperatures-A general review. *Fire Safety Journal*, 13(1), 55–68.

Both, C., van de Haar, P. W., Tan, G. L., & Wolsink, G. M. (1999). Evaluation of passive fire protection measures for concrete tunnel linings. *International Conference & One Day Seminar* “Tunnel Fires and Escape from Tunnels”, Lyon, France, 5-7 May, 10.

Placido, F. (1980). Thermoluminescence test for fire-damaged concrete. *Magazine Of Concrete Research*, 32(111), 112-116. https://doi.org/10.1680/macr.1980.32.111.112

Gosain, N., Drexler, R., & Choudhuri, D. (2008). Structure magazine Structural Forensics Evaluation and Repair of Fire-Damaged Buildings. https://www.structuremag.org/wp-content/uploads/2014/08/C-STRForensics-Fire-Gosain-Sept081.pdf

Zhou, J., & Wang, L. (2019). Repair of Fire-Damaged Reinforced Concrete Members with Axial Load: A Review. *Sustainability*, 11(4), 963.

Bisby, L. A., Chen, J. F., Li, S. Q., Stratford, T. J., Cueva, N., & Crossling, K. (2011). Strengthening fire-damaged concrete by confinement with fiber-reinforced polymer wraps. *Engineering Structures*, 33(12), 3381–3391.

Fam, A., & Mandal, S. (2006). Prestressed Concrete–Filled Fiber-Reinforced Polymer Circular Tubes Tested in Flexure. *PCI Journal*, 51(4), 42–54.

Hung Lin, C., Tyan Chen, S., & An Yang, C. (1995). Repair of Fire-Damaged Reinforced Concrete Columns [Review of Repair of Fire-Damaged Reinforced Concrete Columns]. *Structural Journal*, 92(4), 406–411.

Seito, A I.; et al. (2008), “A segurança contra incêndio no Brasil”. São Paulo: Projeto. 496 p.

Costa, C. N.; Silva, V. P. (2003), “Dimensionamento de estruturas de concreto armado em situação de incêndio: métodos tabulares apresentados em normas internacionais”. In: V Simpósio EPUSP sobre Estruturas de Concreto, 5, 2003, São Paulo.

Topical Fire research series. (n.d.). Retrieved November 12, 2021, from https://www.usfa.fema.gov/downloads/pdf/statistics/v7i2.pdf

Asyraf, M. R. M., Rafidah, M., Ishak, M. R., Sapuan, S. M., Yidris, N., Ilyas, R. A., & Razman, M. R. (2020). Integration of TRIZ , morphological chart and ANP method for development of FRP composite portable fire extinguisher. *Polymer Composites*, 41(7), 2917–2932.

Hi, C. N., Pansuk, W., & Torres, L. (2015). Flexural Behavior of Fire-Damaged Reinforced Concrete Slabs Repaired with Near-Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) Rods. *Journal of Advanced Concrete Technology*, 13(1), 15–29.

Baharuddin, N. K., Mohamed Nazri, F., Putra Jaya, R., & Abu Bakar, B. H. (2016). Evaluation of bond strength between fire-damaged normal concrete substance and ultra-high-performance fiber-reinforced concrete as a repair material. *World Journal of Engineering*, 13(5)

Lee, W. Y., Syed Husin, S. R., Thangaveloo, T., & Hejazi, F. (2019). Forensic engineering of fire damaged concrete structures – a review–. IOP Conference Series: *Earth and Environmental Science*, 357, 012021.

Kodur, V. K. R. (2005). Guidelines for Fire Resistance Design of High-strength Concrete Columns. *Journal of Fire Protection Engineering*.

Asyraf, M. R. M., Rafidah, M., Ishak, M. R., Sapuan, S. M., Yidris, N., Ilyas, R. A., & Razman, M. R. (2020). Integration of TRIZ , morphological chart and ANP method for development of FRP composite portable fire extinguisher. *Polymer Composites*, 41(7), 2917–2932.

Repair of Fire-Damaged Reinforced Concrete Columns. (1995). *ACI Structural Journal*, 92(4). https://doi.org/10.14359/992

Guerrieri, M., & Fragomeni, S. (2013). An experimental investigation into the influence of specimen size, in-situ pore pressures and temperatures on the spalling of difference size concrete panels when exposed to a hydrocarbon fire. *MATEC Web of Conferences*, 6, 01002.

Lin, C. H., Chen, S. T., & Yang, C. A. (1995). Repair of fire damaged reinforced concrete columns. *ACI Structural Journal*, 92(4), 406–411.

Knyziak, P., Kowalski, R., & Krentowski, J. (2019). Fire damage of RC slab structure of a shopping center. *Engineering Failure Analysis*, 97, 53-60. https://doi.org/10.1016/j.engfailanal.2018.12.002M.B.

Dwaikat, M., & Kodur, V. (2009). Fire Induced Spalling in High Strength Concrete Beams. *Fire Technology*, 46(1), 251-274. https://doi.org/10.1007/s10694-009-0088-6

Chudzik, P., Kowalski, R., & Abramowicz, M. (2017). Strains of Concrete in RC Structures Subjected to Fire. *Procedia Engineering*, 193, 377-384. https://doi.org/10.1016/j.proeng.2017.06.227

Kowalski, R., & Wróblewska, J. (2018). Application of a Sclerometer to the Preliminary Assessment of Concrete Quality in Structures After Fire. *Archives Of Civil Engineering*, 64(4), 171-186. https://doi.org/10.2478/ace-2018-0069