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Experimental Study on the Influence of Elevated Temperature on the Mechanical Properties of Concrete Using Crumb Rubber as Partial Replacement of Fine Aggregate and Corrugated Round Steel Fibers

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***Abstract:** The global scientific research circle and government agencies face a number of serious environmental challenges, one of which is the recycling of "End of Life Tires" (ELT). An estimation of one billion tires is expected to end their useful life annually, of which only roughly 50% are recycled at the moment, with the remainder ending up in landfills. Consequently, to solve this gap in the ELT's utilization rate, it is imperative to enhance the current application and furthermore create new applications for recycled tire materials. One of such areas that is currently being investigated is the introduction of waste tire into concrete as partial replacement of natural aggregates in concrete production. This experimental study investigated the influence of elevated temperatures on the mechanical properties of M25 grade concrete, specifically its compressive strength, split tensile strength, and flexural strength. The study focused on the effect of incorporating crumb rubber as a partial replacement of fine aggregate at varying percentages 5%, 10%, 15%, and 20% along with a constant 2% of corrugated round steel fibers. After a standard 28 days water curing period, concrete specimens were subjected to a range of elevated temperatures 200^{0}C, 400^{0}C, 600^{0}C, and 800^{0}C, to simulate fire-like conditions.*

*The results of the study revealed a significant and consistent reduction in all three mechanical properties as the exposure temperature increased, which is a common characteristic of concrete under thermal stress. However, the performance varied notably among the different mixes. For compressive and flexural strength, the concrete mix with 10% crumb rubber (CR) demonstrated superior performance, consistently retaining the highest residual strengths at higher temperatures compared to all other mixes. This finding suggests that a 10% replacement level strikes an optimal balance, where the crumb rubber helps to relieve internal thermal stresses through its melting and decomposition, while the steel fibers provide crucial internal reinforcement to prevent catastrophic failure. In contrast, the split tensile strength tests showed a different trend. The mix with 5% crumb rubber exhibited the best performance at all temperatures. This indicates that while the steel fibers effectively bridged cracks and enhanced tensile properties, higher percentages of crumb rubber led to a greater number of weak bonds within the concrete matrix, which negatively impacted its tensile strength. The study concludes that the strategic incorporation of crumb rubber and steel fibers can enhance the thermal performance of concrete, but the optimal percentage of crumb rubber is dependent on the specific mechanical property being optimized. The findings also led to recommendations for preventive measures against fire damage in concrete, such as the use of fire-resistant mixes, application of protective coatings, and ensuring adequate concrete cover over reinforcement.***

***Keywords:** Concrete, Crumb Rubber, Corrugated Round Steel Fibers, Compressive Strength, Split Tensile Strength, Flexural Strength, etc.*

I. INTRODUCTION

Concrete with its reliable properties like easy availability of constituent materials, mouldability i.e. capacity to acquire any desired shape when it is in the fresh state, durability, and better thermal resistance, it is widely used as a major constituent in infrastructure development. Not only the buildings constructed in wood suffering from fire damage but also the buildings constructed in reinforced concrete are the examples of fire damage despite its good fire resisting properties.

This is because of a change in its mechanical properties due to the change in its physical and chemical composition. According to the report of India Risk Survey 2024, out of top twelve risks from the business perception and functioning in the country, from the past three years, fire risk has been incorporated in the top five risks. Industry-wise risk of fire was observed to be greater in education, hospitality, and infrastructure. The damage extent depends on the design of the structure, fire extinguishing devices, and evacuation process. In India, majority of fires caused due to electric short circuits, gas leakage, and fireworks and due to other causes. Fire and Safety Association of India (FSAI) revealed the fact that India almost losses the assets of USD 100 billion and 20,000 people per year due to fire. In the Maharashtra fire incidences are 20% of the overall country, and this value is greater than any of the state in India.

The research of the National Fire Protection Association (NFPA), a leading association in the United States, indicated that the United States Fire Department responses after every 24 seconds to fire somewhere in the nation. In that, 72% of fire is the structure fires that occurred in homes. Fire incidences in the home structures were increased with 5% from the previous year and in the year 2024 NFPA reported almost the loss of USD 23 billion as a result of the fire. Fire may occur at any time during the entire life span of the structure and it may occur during construction stage also. Most of the fire-damaged structures do not lose its strength completely and that only 9% RCC structures lose their entire strength hence, they can be demolished but, rest of 91% can be repairable. Hence, demolishing the entire structure may not prove to be an economical decision. Thus it is practiced to repair or retrofit the fire damaged structures by using different retrofitting techniques available in the construction field. Before retrofitting it is necessary for the engineer to evaluate the residual strength of fire damaged concrete members. Residual strength of fire damaged concrete may be evaluated by using destructive, partially destructive as well as non-destructive tests. Correlation established between destructive and non-destructive test may be used for calculating the residual strength of concrete.

A. Crumb Rubber

Crumb rubber is recycled rubber produced by grinding down scrap tires into small granules. It's a versatile material used in various applications, including asphalt, sports surfaces, and Crumb rubber is derived from end-of-life tires and is the smallest and highest end use of recycled rubber. Crumb ranges in size from incredibly small particles that are almost dust-like, to roughly a ½” in size. Most of the crumb rubber used in the world is known as 10:20 mesh, which is about the size of a particle of sand. As an aside, mesh size is used as a descriptor and designates how many holes per square inch in the screens used for sizing. A 10:20 product means there are 10 holes on the top screen and 20 holes on the bottom screen, both per square inch. The material in that setup would produce 10:20 mesh which is all the material captured in the middle between the two screens.

Crumb rubber can come from a variety of types of tires but for this discussion let’s look at crumb rubber made from tires like one’s on your vehicle. When a tire is recycled more than just rubber is reclaimed from a vehicle tire. Vehicle tires have steel belts and fiber used to reinforce the tire and give it greater longevity on the road. Both components are recycled into other products and uses as well. As the tires go through the grinding process into smaller and smaller pieces, steel and fiber is removed during the process. This is called ambient grinding. The smaller the rubber particle, the more steel and fiber is removed and given a second life. But grinding a tire is not the only way to break the tire down into crumb rubber.

Fig. 1 Crumb Rubber

B. Corrugated Round Steel Fibers

Corrugated round steel fibers are short, crimped pieces of steel wire added to concrete to enhance its strength, durability, and resistance to cracking. They act as internal reinforcement, improving the concrete's ability to withstand tensile and shear forces. These fibers are designed with a deformed profile to improve bonding with the concrete matrix, leading to better overall performance.

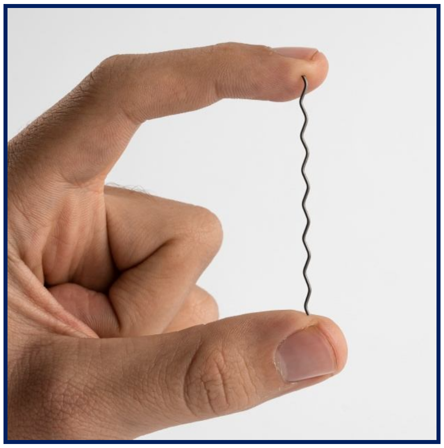

Fig. 2 Corrugated Round Steel Fibers

II. METHODOLOGY

A. Problem Statement

The main objective of this work is to investigate influence of elevated temperature on the mechanical properties of concrete containing granite waste as a coarse aggregate and corrugated round steel fibers. The disposal of granite waste might cause many serious environmental issues. Due to the low reactivity of this aluminosilicate material in its natural state, granite waste was activated through alkali fusion with different amounts of sodium hydroxide. The escalating global accumulation of waste tire rubber presents a pressing environmental challenge, simultaneously driving the construction industry to seek sustainable and high-performance material alternatives. While the integration of crumb rubber into concrete offers promising environmental benefits and can enhance certain ambient mechanical and acoustic properties, a significant knowledge gap persists regarding its comprehensive behavior, particularly concerning its mechanical properties when exposed to varying elevated temperatures. Existing research often lacks systematic experimental investigations across a wide range of temperatures and diverse crumb rubber replacement percentages for multiple mechanical characteristics. Crucially, the precise mechanisms by which crumb rubber influences the thermal stability, spalling resistance, and residual strength of concrete under fire conditions remain insufficiently understood and inconsistently reported. Therefore, this experimental study aims to address this critical gap by thoroughly investigating the influence of elevated temperatures on the compressive strength, tensile strength and flexural strength of concrete utilizing crumb rubber as a partial replacement for fine aggregate and corrugated round steel fibers, thereby providing vital data for its confident and safe application in fire-resilient structural design and contributing to the development of relevant material standards.

B. Aim of the Study

The main aim of the study is to:

1) Evaluate the changes in key mechanical properties (including compressive strength, splitting tensile strength and flexural strength) of crumb rubber concrete after exposure to various elevated temperature regimes.
2) Determine the optimal or effective replacement percentages of crumb rubber that maintain acceptable mechanical performance under elevated temperatures.
3) Provide crucial experimental data that contributes to a better understanding of the fire performance of crumb rubber concrete, thereby facilitating its confident and safe application in fire-resilient structural designs.
4) Contribute valuable insights that can inform the development of relevant material standards and guidelines for sustainable concrete construction.

C. Limitations of the Study

1) This study will primarily focus on laboratory-scale experimental testing and will not involve real-scale fire tests on structural elements.
2) The long-term durability of crumb rubber concrete after thermal exposure (e.g., long-term resistance to environmental factors, sustained load capacity over extended periods after cooling) will not be the primary focus.
3) Detailed economic feasibility analysis or a comprehensive life cycle assessment (LCA) of crumb rubber concrete will be outside the direct scope.
4) The study may not cover the influence of different crumb rubber particle sizes or shapes, or various surface treatment methods for crumb rubber, unless specified as a variable within the selected mix designs.

D. Objectives of the Study

The objectives of this research are:

1) To study the effect of elevated temperature on compressive strength of concrete containing crumb rubber as partial replacement of fine aggregate by 5%, 10%, 15%, 20% and 2% of corrugated round steel fibers for 28 days of water curing for M25 grade of concrete,
2) To study the effect of elevated temperature on split tensile strength of concrete containing crumb rubber as partial replacement of fine aggregate by 5%, 10%, 15%, 20% and 2% of corrugated round steel fibers for 28 days of water curing for M25 grade of concrete,
3) To study the effect of elevated temperature on flexural strength of concrete containing crumb rubber as partial replacement of fine aggregate by 5%, 10%, 15%, 20% and 2% of corrugated round steel fibers for 28 days of water curing for M25 grade of concrete,
4) To provide preventive measures for fire damaged concrete.

E. Methodology of the Work

The different phases of this project of work are shown in the following diagram. The figure simply describes the experimental strategy of this study step by step.

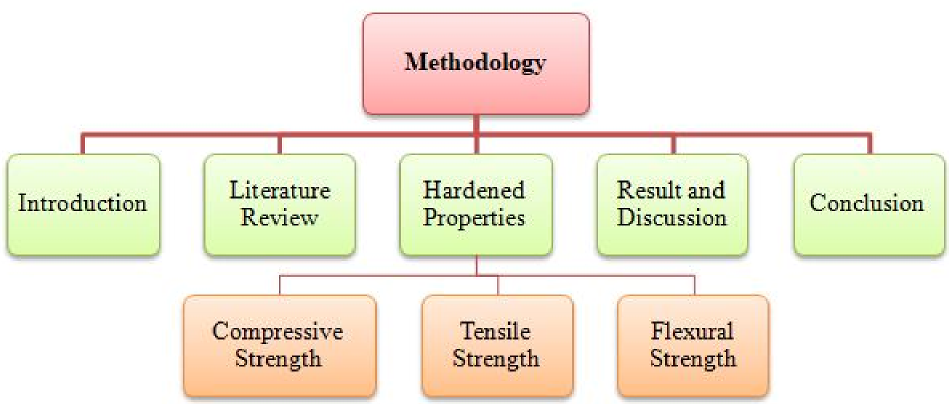

Fig. 3 Methodology Flow Chart

F. Fires on Concrete

Fire on concrete brings mineralogical and strength changes in the concrete. From the literature, it was observed that up to 105°C temperature minor loss in strength which are smaller than 10% of the overall strength by forming capillary porosity and minor micro cracking due to loss of physically bound water. Around 300°C temperature oxidation of iron compounds starts that results in pink/red discoloration of aggregate which causes significant loss in strength after 300°C temperature. α to β quartz transition phase was observed between the temperature 600-800°C and specifically at the temperature 573°C, this phenomenon is also called an inversion. Here α to β transition phase refers to an abrupt change in the volume of quartz crystals when they are heated from stable room temperature i.e. from α crystal phase to the temperature above 573°C which brings β crystal phase in quartz. After heating to 600°C concrete does not remain structurally useful.

Fig. 4 Fires on Building

Within 600-800°C temperature, if the calcareous aggregate is used, that imparts significant contraction in concrete by releasing carbon-dioxide which brings severe micro-cracking in the matrix of cement. Heating of the concrete up to 1200°C imparts whitish grey coloration caused due to dissociation and extreme thermal stress, caused due to the disintegration of calcareous constituents of aggregate and cement matrix. In addition to the above parameters, the shape of the specimen with the available surface area for uniform heating and relatively small size of the specimen, it was decided to heat the early age concrete up to the peak temperature 400°C, 600°C and 800°C to study the strength changes in concrete. After curing of the concrete specimens for 28 days they were kept in the electric muffle furnace with the electronic controller in the SSD condition. Before heating, a damp cloth was used to wipe off the surface water.

III.EXPERIMENTAL STUDY

A. Summary of Test Results on Cement

TABLE I
TEST RESULTS ON CEMENT

Sr. No.	Description of Test	Results
1	Fineness of cement (Residue on IS sieve No.9)	2.54 %
2	Specific Gravity	3.15
3	Standard consistency of cement	30 %
4	Setting time of cement a) Initial Setting Time b) Final Setting Time	 40 min. 584 min.
5	Soundness test of cement (with Le-chatelier's mould)	8.0 mm
6	Compressive Strength of Cement (28 Days of curing)	53.87 N/mm^2

B. Summary of Test Results on Aggregates

TABLE III
TEST RESULTS ON AGGREGATES

Sr. No.	Property	Results of Fine Aggregates	Results of Coarse Aggregates
1	Particle Shape, Size	Round, 4.75 mm down	Angular, 10 mm down
2	Fineness Modulus	2.683	6.0
3	Silt Content	3.3 %	4 %
4	Specific Gravity	2.94	2.69
5	Bulk Density	1723 kg/m^3	1620 kg/m^3
6	Surface Moisture	Nil	Nil

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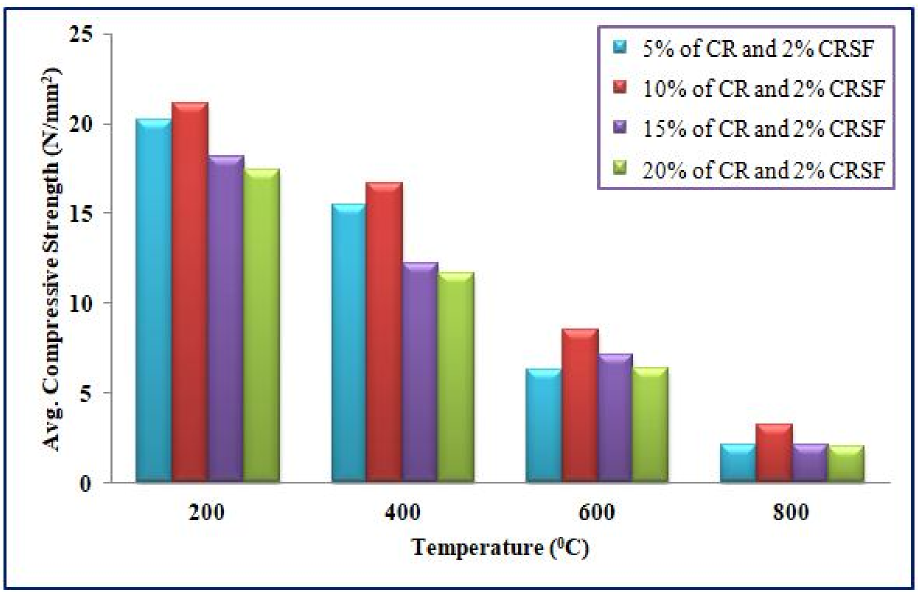
C. Results of Compressive Strength on Concrete

A compression testing machine (CTM) is used to test the mechanical properties (tension, compression etc.) of a given test specimen by exerting tensile, compressive or transverse stresses. The machine has been named so because of the wide range of tests it can perform over different kind of materials. Different tests like peel test, flexural test, tension test, bend test, friction test, spring test etc. can be performed with the help of CTM.

TABLE IIIII
Summary Results of Compressive Strength Test of Concrete for 28 Days of Curing with 5%, 10%, 15% and 20% of Crumb Rubber and 2% of Corrugated Round Steel Fibers

Sr. No.	Temp.	Avg. Compressive Strength (N/mm^2) (2% CRSF)			
		5% of CR	10% of CR	15% of CR	20% of CR
1	200 ^{0}C	20.15	21.10	18.17	17.40
2	400 ^{0}C	15.45	16.68	12.17	11.67
3	600 ^{0}C	6.30	8.48	7.13	6.33
4	800 ^{0}C	2.07	3.22	2.10	1.97

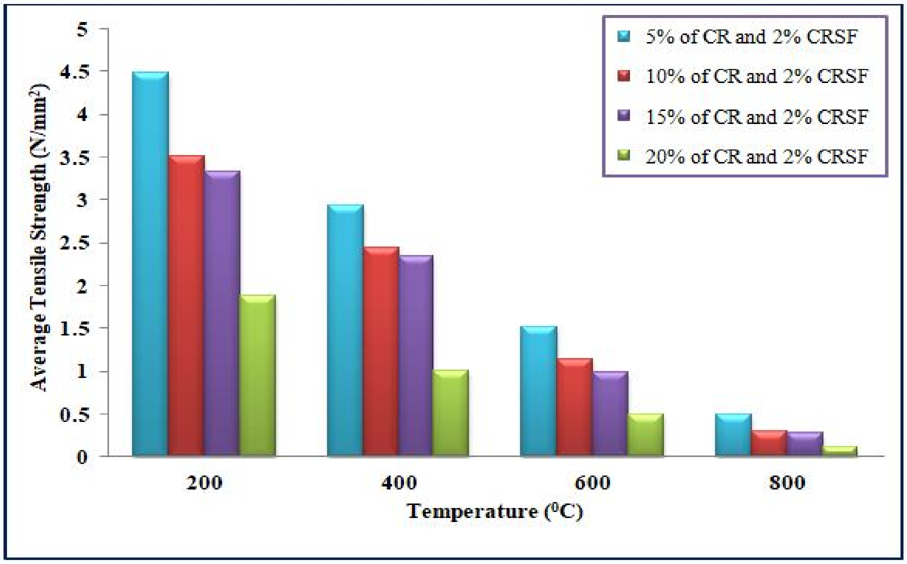


Graph 1: Summary Results of Compressive Strength Test of Concrete for 28 Days of Curing with 5%, 10%, 15% and 20% of Crumb Rubber and 2% of Corrugated Round Steel Fibers

D. Results of Split Tensile Strength on Concrete

TABLE IVV
Summary Results of Split Tensile Strength Test of Concrete for 28 Days of Curing with 5%, 10%, 15% and 20% of Crumb Rubber and 2% of Corrugated Round Steel Fibers

Sr. No.	Temp.	Avg. Split Tensile Strength (N/mm^2) (2% CRSF)			
		5% of CR	10% of CR	15% of CR	20% of CR
1	200 ^{0}C	4.47	3.5	3.33	1.87
2	400 ^{0}C	2.93	2.43	2.33	1.00
3	600 ^{0}C	1.52	1.13	0.98	0.50
4	800 ^{0}C	0.50	0.30	0.27	0.12



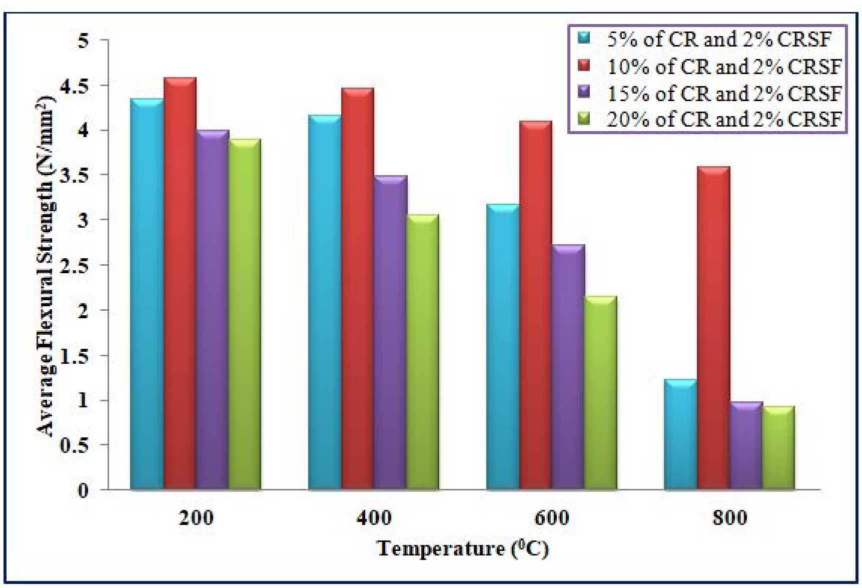
Graph 2: Summary Results of Split Tensile Strength Test of Concrete for 28 Days of Curing with 5%, 10%, 15% and 20% of Crumb Rubber and 2% of Corrugated Round Steel Fibers

E. *Results of Flexural Strength on Concrete*

TABLE V

Summary Results of Flexural Strength Test of Concrete for 28 Days of Curing with 5%, 10%, 15% and 20% of Crumb Rubber and 2% of Corrugated Round Steel Fibers

Sr. No.	Temp.	Avg. Flexural Strength (N/mm^2) (2% CRSF)			
		5% of CR	10% of CR	15% of CR	20% of CR
1	200 ^{0}C	4.33	4.57	3.99	3.88
2	400 ^{0}C	4.15	4.46	3.48	3.05
3	600 ^{0}C	3.17	4.08	2.72	2.15
4	800 ^{0}C	1.22	3.58	0.97	0.92



Graph 3: Summary Results of Flexural Strength Test of Concrete for 28 Days of Curing with 5%, 10%, 15% and 20% of Crumb Rubber and 2% of Corrugated Round Steel Fibers

F. Preventive Measure for Concrete from Fire

Fire resistance of concrete is considered one of the most important properties which protect life, property and the environment in the case of fire. It responds effectively to all the protective aims of safety and serviceability of building construction, benefiting everyone from building users, owners, businesses and residents to insurers, regulators and fire-fighters. Whether it is used for residential buildings, industrial warehouses or tunnels work, concrete can be designed and specified to remain robust even in the most extreme fire situations.

Compare to the other materials, fire resistance of concrete is very high and that is due to the following reasons:

1) Concrete does not burn itself and hence does not contribute to fire load on the structure.
2) Due to the high fire resistance of concrete, spread of fire is prevented ab initio, unlike wood.
3) Concrete is a very good fire barrier, which ensures the easy escape routes with proper functional design
4) Concrete does not melt, which otherwise would enhance spread of fire or invite collapse of building.
5) Concrete does not produce smoke and toxic gases, thereby reducing the risk to personnel and fire-fighters during fire.
6) Concrete holds the fire in, thereby reducing its spread to the surroundings
7) Concrete acts as a fire protective material by itself; hence, under normal circumstances, no additional measures, materials, and expertise is required in the construction.
8) Concrete has an extremely high resilience to extreme temperatures, which makes it an ideal material for housing or storage areas that contain large fire loads.
9) Concrete maintains integrity of the structure during the fire generation and extinction phases without the development of large deformations and overall movement of the structure or the individual spans, thereby facilitating the process of fire extinction without fear or worry of collapse.
10) Concrete used in tunnels as a paving material in contrast to asphalt which is a combustible and plastic material during a fire, ensures that the fire will not spread inside the tunnel. In addition, the fact that concrete retains its rigidity will makes it possible to intervene immediately during fire fighting to evacuate the personnel, without allowing for time for the pavement to cool.
11) Concrete used in buildings in urban environments prevent the spread of fire to adjoining buildings.
12) Due to the less thermal movements during the fire, it is ensured that the structure will not destabilize and/or collapse and also ensures that it will restrict spreading of fire due to loss of the barriers between the compartments.
13) Concrete is not adversely affected by the water thrown on it during the fire
14) Concrete can be easily repaired after the fire, thus saving both time and costs during rehabilitation works after fire, and hence structure can be readily put to use.

Fig. 5 Windsor Tower in Madrid

The Windsor Tower in Madrid is a very good case of a modern high-rise building exposed to fire. The building had a burning concrete structure (slabs, shear wall cores, and interior columns) and perimeter columns of steel. It was destroyed by fire in 2005 which started on the 21st floor (out of 29 floors in total) and lasted 25 hours.

The use of strong deep reinforced concrete Beam in the floors, as well as the remaining vertical load-bearing concrete elements (shear wall cores and columns), controlled the complete fall or collapse of the structure and gave an extremely long duration for resistance of the fire to the structure. While the world trade centre tower which was hit by plances caused fire which resulted in burning of steel collapse, thus invited fast spread of fire resulting in total collapse of building. If perhaps, there would have been concrete column, it might have given some time to occupant to come out and save their life.

To enhance concrete's fire resistance, consider using fire-resistant concrete mixes, applying protective coatings like intumescent paints or lightweight mortar, and ensuring adequate concrete cover over reinforcement.

1) Fire-Resistant Concrete Mixes:

a. Mineral Admixtures and Fibers: Incorporating mineral admixtures and fibers into the concrete mix can improve its thermal properties and resistance to high temperatures.

b. Low Heat Cement: Using low-heat cement, which generates less heat of hydration, is beneficial for constructing massive concrete structures, minimizing the risk of thermal deformation.

2) Protective Coatings:

a. Intumescent Paints: Applying a heat-resistant coating like intumescent paint can create a protective layer that swells and expands upon exposure to fire, insulating the concrete.

b. Lightweight Mortar: Applying a layer of lightweight mortar to exposed concrete surfaces can provide a physical barrier and insulate the concrete from heat.

c. Board Systems: Protecting concrete surfaces with board systems made from fire-resistant materials can also be effective.

3) Adequate Concrete Cover:

a. Reinforcement Protection: Ensuring adequate concrete cover over reinforcement (steel bars) is crucial to protect it from high temperatures during a fire.

b. Construction Practices: Following good construction practices that ensure the quality and durability of structural elements, such as avoiding excessive compaction or curing that can increase density, and avoiding voids, cracks, or defects that can trap moisture, is important.

4) Other Considerations:

a. Compartmentation: Dividing a building into fire-resistant compartments can help contain the spread of fire.

b. Fire Safety Measures: Implementing fire safety measures like fire alarms, sprinklers, and smoke detectors is crucial.

c. Regular Inspections and Maintenance: Regularly inspecting and maintaining concrete structures can help identify and address potential vulnerabilities.

d. Understanding Building Risks: Understanding the specific risks associated with a building's use and location is important for implementing appropriate fire safety measures.

By implementing these preventive measures, the risk of fire damage to concrete structures can be significantly reduced, enhancing the safety of buildings and their occupants.

IV. CONCLUSIONS

The following summarizes the conclusions of the study.

1) The effect of elevated temperatures on the compressive strength of M25 concrete reinforced with 2% corrugated steel fibers and incorporating 5%, 10%, 15%, and 20% crumb rubber with elevated temperatures shows significant decrease in compressive strength for all mixes as the temperature rises. However, the concrete mix with 10% crumb rubber demonstrated the best performance, retaining the highest residual strength at 600^0C (8.48 N/mm^2) and 800^0C (3.22 N/mm^2). This indicates that the 10% crumb rubber, combined with the steel fibers, provided an optimal balance for mitigating thermal stress and maintaining structural integrity at high temperatures. In contrast, higher crumb rubber percentages (15% and 20%) resulted in lower strengths, likely due to excessive void formation. In summary, the use of 10% crumb rubber and 2% steel fibers is an effective strategy for enhancing the thermal performance and residual strength of M25 grade concrete.

2) The split tensile strength of concrete containing crumb rubber and steel fibers with elevated temperatures has drastically reduced. The data shows that the mix with 5% crumb rubber retained the highest split tensile strength at all temperatures, outperforming the mixes with higher crumb rubber percentages. Specifically, while the 5% crumb rubber mix started at 4.47 N/mm^2 at 200^0C, it still maintained a strength of 0.50 N/mm^2 even at 800^0C. In contrast, the mixes with 10%, 15%, and 20% crumb rubber showed progressively lower tensile strengths. This indicates that increasing the crumb rubber content has a negative effect on tensile strength, despite the reinforcing action of the steel fibers. In summary, the optimal balance for maintaining split tensile strength at elevated temperatures is achieved with a lower crumb rubber percentage of 5%.

3) This study found that elevated temperatures significantly reduce the flexural strength of concrete containing crumb rubber and steel fibers. The data shows that the mix with 10% crumb rubber retained the highest strength across all temperatures, with a strength of 3.58 N/mm^2 at 800^{0}C. This indicates that the 10% crumb rubber, combined with the steel fibers, provided an optimal balance for mitigating thermal stress. Conversely, mixes with higher crumb rubber content (15% and 20%) showed much lower strengths, suggesting that an excessive amount of crumb rubber introduced too many weak points into the concrete. In summary, the strategic use of 10% crumb rubber and 2% corrugated steel fibers is an effective approach to enhancing the flexural strength and overall performance of concrete under thermal stress.

4) The concrete can be prevented by enhancing concrete's fire resistance using fire-resistant concrete mixes, applying protective coatings which heat-resistant coating like in tumescent paint can create a protective layer that swells and expands upon exposure to fire or lightweight mortar, and ensuring adequate concrete cover over reinforcement, insulating the concrete and concrete surfaces with board systems made from fire-resistant materials can also be effective.

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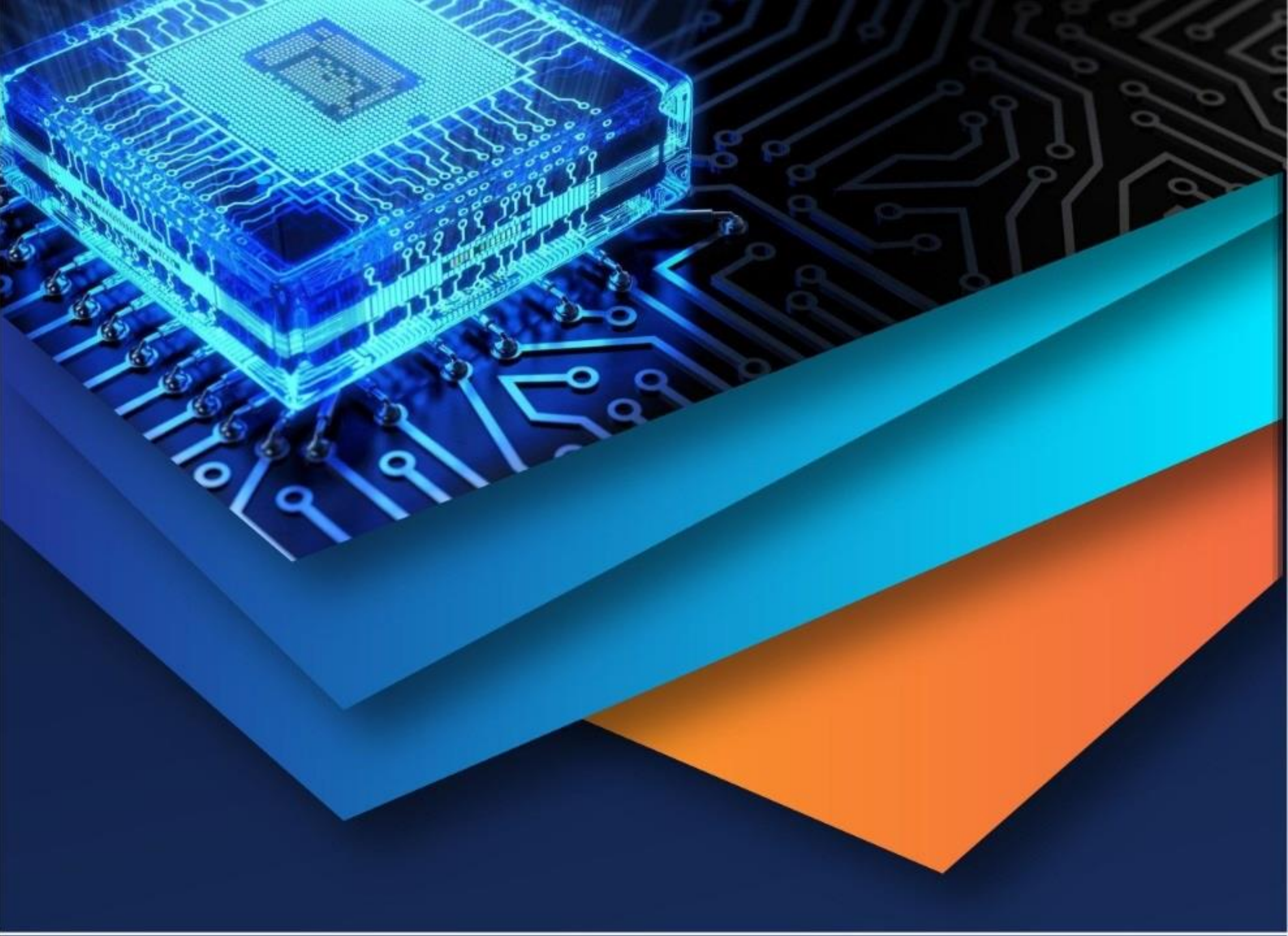

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