Thermo-Structural Response and Mechanical Property Degradation of Reinforced Cement Concrete at Elevated Temperatures: A Review

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Abstract—
Reinforced Cement Concrete (RCC) is one of the most widely used construction materials because of its strength, durability, and cost-effectiveness. However, exposure to elevated temperatures during fire and other extreme thermal events significantly degrades its structural performance. This review presents a comprehensive assessment of the thermo-structural behaviour and mechanical property degradation of RCC under high-temperature conditions. It discusses the thermal properties of concrete and reinforcing steel, mechanisms of heat transfer, and the development of thermal stresses affecting structural stability. The review examines the deterioration of compressive, tensile, flexural, and bond strengths of concrete, along with reductions in the mechanical properties of reinforcing steel at elevated temperatures. It also analyses the behaviour of RCC beams, columns, slabs, and walls, considering factors such as concrete composition, aggregate type, moisture content, heating conditions, reinforcement ratio, and fibre incorporation. Advanced microstructural characterization techniques, are reviewed to explain the relationship between microstructural damage and mechanical degradation. Furthermore, the paper evaluates experimental methods, numerical modelling approaches, and international fire design standards. Finally, key research gaps and future directions are identified to improve fire-resistant design, post-fire assessment, and the development of durable and sustainable RCC structures under elevated temperature conditions.

Keywords— Reinforced Cement Concrete (RCC); Elevated Temperature; Thermo-Structural Response; Mechanical Property Degradation; Fire Resistance; Residual Strength; Thermal Damage; Structural Fire Engineering

I. INTRODUCTION

Reinforced Cement Concrete (RCC) has become the backbone of modern civil engineering owing to its excellent compressive strength, durability, versatility, and cost-effectiveness. It is extensively used in the construction of residential buildings, commercial complexes, industrial facilities, bridges, tunnels, dams, power plants, and other critical infrastructure. The combination of concrete and reinforcing steel provides superior structural performance, enabling RCC structures to resist both compressive and tensile forces effectively. Under normal environmental conditions, RCC exhibits remarkable serviceability and long-term durability. However, its structural performance can deteriorate significantly when exposed to elevated temperatures during fire incidents or other extreme thermal conditions.

Fire hazards represent one of the most severe threats to reinforced concrete structures. Urbanization, industrial development, and the increasing complexity of modern infrastructure have substantially increased the risk of accidental fires in buildings, tunnels, petrochemical plants, nuclear facilities, and transportation systems. During a fire, temperatures may exceed 1000°C, causing rapid heating of structural members. Such thermal exposure results in dehydration of cement hydration products, thermal expansion, moisture migration, microcrack formation, loss of bond between concrete and reinforcing steel, explosive spalling, and considerable reductions in mechanical properties. Simultaneously, reinforcing steel experiences reductions in yield strength, elastic modulus, and ductility, thereby weakening the composite action that is fundamental to RCC performance. These changes may ultimately reduce the load-bearing capacity, serviceability, and fire resistance of structural members, increasing the likelihood of structural failure.

The thermo-structural response of RCC is governed by complex interactions between thermal, mechanical, and material properties. Heat transfer through conduction, convection, and radiation generates non-uniform temperature distributions within concrete members, leading to thermal gradients and restrained thermal strains. The mismatch in thermal expansion coefficients of concrete and reinforcing steel produces internal stresses that accelerate crack propagation and structural deformation. Furthermore, factors such as concrete strength grade, aggregate type, water-cement ratio, moisture content, heating rate, duration of exposure, cooling method, and reinforcement configuration significantly influence the extent of thermal degradation. Therefore, understanding these coupled mechanisms is essential for accurately predicting structural behaviour during and after fire exposure.

In recent decades, extensive research has been conducted to investigate the behaviour of reinforced concrete under elevated temperatures using laboratory experiments, microstructural characterization techniques, analytical formulations, and advanced numerical simulations. Modern computational tools, including finite element modelling, have further enhanced the capability to predict thermo-mechanical performance under realistic fire scenarios. Nevertheless, differences in testing methodologies, material compositions, and fire exposure conditions often lead to variations in reported results, highlighting the need for a comprehensive synthesis of existing knowledge.

The primary objective of this review is to critically examine the thermo-structural response and mechanical property degradation of reinforced cement concrete subjected to elevated temperatures. The review discusses heat transfer mechanisms, thermal damage processes, degradation of concrete and reinforcing steel, microstructural transformations, fire-induced spalling, residual mechanical properties, and numerical modelling approaches. It also evaluates relevant international fire design standards and identifies current research gaps and future directions. By integrating findings from recent experimental, analytical, and computational studies, this review aims to provide researchers, structural engineers, and practicing professionals with a comprehensive understanding of the behaviour of RCC under high-temperature conditions, thereby supporting the development of safer, more resilient, and fire-resistant concrete infrastructure.

II. LITERATURE REVIEW

ecent research on reinforced cement concrete (RCC) exposed to elevated temperatures has shifted from conventional strength evaluation to integrated thermo-mechanical, microstructural, and computational analyses. Advances in experimental techniques, material technology, and numerical modelling have significantly improved the understanding of fire-induced deterioration and the prediction of structural performance. Modern studies emphasize the coupled interaction between heat transfer, moisture migration, mechanical loading, and chemical degradation, providing a more realistic representation of RCC behaviour under fire conditions.

One of the most significant developments has been the use of advanced fibre-reinforced concretes. Polypropylene fibres are widely recognized for their ability to reduce explosive spalling by melting at temperatures around 160–170°C, thereby creating channels for the release of water vapour and reducing internal pore pressure. Steel fibres, on the other hand, enhance residual tensile strength, crack resistance, and post-fire load-carrying capacity. Hybrid fibre systems combining polymeric and steel fibres have demonstrated superior fire resistance by simultaneously improving ductility, toughness, and thermal stability.

Considerable attention has also been directed toward high-performance concrete (HPC), ultra-high-performance concrete (UHPC), geopolymer concrete, and recycled aggregate concrete. While these materials exhibit excellent mechanical properties under ambient conditions, their response to elevated temperatures varies depending on binder composition, aggregate type, fibre content, and moisture characteristics. Recent studies indicate that optimized fibre reinforcement and supplementary cementitious materials can improve residual strength and fire resistance, although additional research is required to establish standardized design recommendations.

Modern characterization techniques have greatly enhanced the understanding of thermal degradation mechanisms. Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), Fourier Transform Infrared Spectroscopy (FTIR), Mercury Intrusion Porosimetry (MIP), and X-ray Computed Tomography (micro-CT) enable detailed evaluation of pore development, crack propagation, interfacial transition zone deterioration, and decomposition of hydration products. These techniques have established direct relationships between microstructural damage and reductions in compressive strength, elastic modulus, and durability after fire exposure.

III. FUNDAMENTALS OF REINFORCED CEMENT CONCRETE

Reinforced Cement Concrete (RCC) is one of the most widely used construction materials because it combines the high compressive strength of concrete with the excellent tensile strength of steel reinforcement. This composite material has revolutionized the construction industry by enabling the development of durable, economical, and structurally efficient buildings, bridges, dams, tunnels, and other infrastructure. The superior performance of RCC is attributed to the complementary properties of its constituent materials, which work together to resist various types of loading under normal and extreme environmental conditions.

3.1 Constituents of Concrete

Concrete is a composite material consisting primarily of cement, fine aggregates, coarse aggregates, water, and, in many cases, chemical or mineral admixtures. Ordinary Portland Cement (OPC) acts as the binding material that reacts with water through the process of hydration to form calcium silicate hydrate (C-S-H) gel, the principal compound responsible for the strength and durability of concrete. Fine aggregates, generally natural sand or manufactured sand, fill the voids between coarse aggregates and contribute to workability and surface finish. Coarse aggregates, such as crushed stone or gravel, provide bulk volume and significantly influence the compressive strength, stiffness, and thermal stability of concrete. Water is essential for cement hydration and determines the workability of fresh concrete. The water-cement ratio is one of the most important parameters affecting the strength, permeability, and durability of hardened concrete. Modern concrete mixtures also incorporate supplementary cementitious materials such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS), along with chemical admixtures, to improve workability, strength development, and resistance to aggressive environments.

3.2 Role of Reinforcement

Concrete possesses excellent compressive strength but exhibits very low tensile strength, making it susceptible to cracking under tensile loading. Steel reinforcement is therefore embedded within concrete to resist tensile stresses and improve the structural performance of RCC members. Reinforcing steel bars provide ductility, increase load-carrying capacity, control crack propagation, and enhance structural stability during both service and ultimate loading conditions. The compatibility between steel and concrete is achieved because both materials have similar coefficients of thermal expansion, allowing them to expand and contract together under temperature variations without inducing excessive internal stresses under normal conditions. Furthermore, the alkaline environment created by concrete provides a protective passive layer around the reinforcing steel, reducing the risk of corrosion. Adequate bond strength between concrete and steel ensures efficient transfer of stresses, enabling RCC structures to behave as a single composite unit.

3.3 Mechanical Properties under Ambient Conditions

Under ambient temperature conditions, the mechanical performance of RCC depends on the properties of both concrete and reinforcing steel. The compressive strength of normal concrete generally ranges from 20 MPa to over 60 MPa, depending on the mix design and curing conditions. Tensile strength is approximately 8–12% of the compressive strength, while flexural strength is influenced by aggregate characteristics and reinforcement. The modulus of elasticity of concrete typically varies between 20 and 40 GPa and determines its resistance to deformation under applied loads. Reinforcing steel exhibits high tensile strength, commonly ranging from 415 to 600 MPa, together with significant ductility, allowing structural members to undergo deformation before failure. Other important mechanical properties include bond strength, fracture toughness, creep resistance, and fatigue performance, all of which contribute to the long-term safety and durability of RCC structures.

3.4 Thermal Properties of Concrete and Steel

The thermal behaviour of RCC is governed by the thermal properties of both concrete and reinforcing steel. Concrete is a relatively poor conductor of heat, with thermal conductivity generally ranging from 1.4 to 3.5 W/m·K depending on aggregate type, density, and moisture content. Its specific heat capacity, approximately 800–1000 J/kg·K, determines the amount of heat required to increase its temperature. Thermal diffusivity controls the rate of heat penetration through the concrete mass, while the coefficient of thermal expansion, typically $8–12 \times 10^{-6}/°C$, governs dimensional changes during heating and cooling. Reinforcing steel has considerably higher thermal conductivity and expands at a coefficient of approximately $12 \times 10^{-6}/°C$. During elevated temperature exposure, these thermal properties influence heat transfer, temperature distribution, thermal strains, and stress development within RCC members. As temperatures increase beyond approximately 300°C, dehydration of cement hydrates, microcrack formation, and degradation of the bond between concrete and steel progressively reduce the structural capacity of RCC. Therefore, a thorough understanding of the fundamental constituents, mechanical characteristics, and thermal properties of reinforced cement concrete is essential for evaluating its thermo-structural response and designing fire-resistant infrastructure.

IV. HEAT TRANSFER MECHANISMS IN REINFORCED CEMENT CONCRETE (RCC)

Heat transfer plays a fundamental role in determining the behaviour of reinforced cement concrete (RCC) structures exposed to elevated temperatures. During fire incidents or high-temperature industrial operations, thermal energy is transmitted from the surrounding environment into concrete members through the combined mechanisms of conduction, convection, and radiation. The rate and pattern of heat transfer significantly influence the temperature distribution within structural elements, which subsequently governs thermal expansion, stress development, material degradation, and the overall structural response. Therefore, understanding heat transfer mechanisms is essential for accurately predicting the fire resistance and post-fire performance of RCC structures.

4.1Conduction is the primary mechanism of heat transfer within concrete and reinforcing steel. It occurs through direct molecular interaction without any movement of the material itself. When one surface of an RCC member is exposed to fire, heat is conducted from the hot exterior toward the cooler interior through the concrete matrix and embedded steel reinforcement. Since concrete has relatively low thermal conductivity (approximately 1.4–3.5 W/m·K), heat penetrates slowly, providing temporary insulation to the inner core of structural members. In contrast, reinforcing steel possesses significantly higher thermal conductivity, enabling heat to spread rapidly along the reinforcement bars. Factors such as concrete density, aggregate type, moisture content, porosity, and temperature influence the rate of conductive heat transfer. At elevated temperatures, thermal conductivity generally decreases due to dehydration, micro cracking, and increased pore formation within the concrete.

4.2 Convection refers to the transfer of heat between the surface of RCC members and the surrounding hot gases during fire exposure. This mechanism occurs through the movement of heated air or combustion gases around the structural element. Natural convection results from density differences caused by temperature variations, whereas forced convection occurs due to external airflow generated by ventilation systems or wind. The efficiency of convective heat transfer depends on gas temperature, flow velocity, surface roughness, and the convective heat transfer coefficient. Although convection primarily affects the external surface of concrete members, it determines the amount of thermal energy available for subsequent conduction into the structure.

4.3 Radiation becomes increasingly significant during severe fire conditions, particularly when temperatures exceed 500°C. Thermal radiation transfers heat in the form of electromagnetic waves and does not require a physical medium. Flames and hot combustion products emit radiant energy that is absorbed by the exposed surface of concrete. The magnitude of radiative heat transfer depends on the surface emissivity, temperature difference between the fire and the concrete surface, and the duration of exposure. Radiation often contributes substantially to the rapid heating of structural elements during the initial stages of a fully developed fire.

Thermo-Structural Response of Reinforced Cement Concrete (RCC)

The thermo-structural response of Reinforced Cement Concrete (RCC) subjected to elevated temperatures is governed by the interaction between thermal loading and the mechanical behaviour of concrete and reinforcing steel. During fire exposure, RCC members experience significant physical, chemical, and structural changes that alter their load-bearing capacity, stiffness, and overall stability. The severity of these changes depends on several factors, including the maximum temperature reached, duration of exposure, heating and cooling rates, moisture content, reinforcement ratio, and the properties of constituent materials. Understanding the thermo-structural response is essential for evaluating fire resistance, predicting structural failure, and designing effective rehabilitation measures for fire-damaged structures.

V.THERMO-STRUCTURAL RESPONSE OF REINFORCED CEMENT CONCRETE (RCC)

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5.1 Thermal Expansion

Thermal expansion is the increase in the dimensions of a material when subjected to elevated temperatures. Both concrete and reinforcing steel expand during heating; however, their expansion behaviour differs due to variations in material composition and thermal properties. Concrete generally exhibits a coefficient of thermal expansion between 8 and 12 × 10^{-6}/°C, while reinforcing steel has a value of approximately 12 × 10^{-6}/°C. Although these values are relatively similar under normal conditions, non-uniform heating and material heterogeneity lead to differential expansion within RCC members. As temperature increases beyond 300°C, dehydration of cement hydrates and aggregate transformations alter the expansion characteristics of concrete, resulting in irreversible deformation and volumetric instability. Excessive thermal expansion may induce significant displacement, reduce structural integrity, and contribute to the initiation of cracks.

5.2 Differential Strain

Differential strain develops when different regions of an RCC member experience unequal temperature increases or when concrete and reinforcing steel deform at different rates. Fire exposure usually creates steep temperature gradients, with the outer surface becoming much hotter than the interior. Consequently, the heated outer layers expand more rapidly than the cooler inner core, generating incompatible deformations. Simultaneously, reinforcing steel, owing to its higher thermal conductivity, heats and expands differently from the surrounding concrete. These incompatible strains create internal restraint forces, which accelerate crack initiation, bond deterioration, and local damage. Differential strain is particularly significant in beams, slabs, and columns exposed to one-sided fire, where temperature gradients are highly pronounced.

5.3 Thermal Stress Development

When thermal expansion is restrained by supports, adjacent structural components, or internal material interactions, thermal stresses develop within RCC members. These stresses are superimposed on the existing mechanical stresses caused by external loads, thereby increasing the likelihood of structural distress. Tensile thermal stresses are especially critical because concrete possesses relatively low tensile strength. As heating progresses, the modulus of elasticity of concrete decreases, reducing its stiffness and increasing susceptibility to deformation. Simultaneously, reinforcing steel loses yield strength and elastic modulus at elevated temperatures, weakening the composite action between steel and concrete. The combined effects of thermal and mechanical loading significantly reduce the load-carrying capacity and fire resistance of RCC structures.

5.4 Cracking Mechanisms

Crack formation is one of the earliest indicators of thermal damage in reinforced concrete structures. Thermal expansion, moisture evaporation, internal vapour pressure, and differential strain collectively contribute to crack initiation and propagation. Initially, fine micro cracks develop within the cement paste and at the interfacial transition zone (ITZ) between cement paste and aggregates. As temperature increases, these micro cracks coalesce into larger cracks that extend through the concrete matrix. Severe thermal exposure may also result in explosive spalling, where layers of concrete detach from the surface, exposing reinforcing steel directly to fire. Such cracking significantly reduces stiffness, bond strength, durability, and residual structural capacity.

5.5 Deflection Behavior

Elevated temperatures substantially increase the deflection of RCC structural members. The reduction in the modulus of elasticity of concrete and steel decreases member stiffness, while thermal expansion generates additional curvature. Beams and slabs are particularly susceptible to excessive sagging under combined thermal and mechanical loads. Long-duration fire exposure may also induce thermal creep, which causes progressive deformation even under constant loading. Excessive deflection can impair serviceability, redistribute internal forces, and ultimately contribute to structural instability or collapse if the residual load-carrying capacity is exceeded.

5.6 Buckling and Instability

Buckling is a critical failure mode for reinforced concrete columns and slender compression members subjected to elevated temperatures. Fire-induced reductions in material strength and stiffness, combined with thermal expansion and increased eccentricity, significantly decrease the critical buckling load. Non-uniform heating often produces asymmetric deformation, causing lateral displacement and additional bending moments. As reinforcing steel loses strength at temperatures above approximately 500–600°C, columns become increasingly vulnerable to instability and progressive failure. Therefore, evaluating buckling behaviour is essential in fire-resistant structural design, as premature instability may occur before complete material degradation. Comprehensive thermo-structural assessment enables engineers to predict failure mechanisms accurately and develop effective fire protection, strengthening, and rehabilitation strategies for reinforced concrete infrastructure.

VI. MECHANICAL PROPERTY DEGRADATION OF REINFORCED CEMENT CONCRETE AT ELEVATED TEMPERATURES

The mechanical properties of reinforced cement concrete (RCC) deteriorate significantly when exposed to elevated temperatures due to a combination of physical, chemical, and microstructural changes occurring within concrete and reinforcing steel. Fire exposure causes dehydration of cement hydration products, thermal incompatibility between aggregates and cement paste, moisture evaporation, pore pressure build-up, and extensive micro cracking. These changes progressively reduce the strength, stiffness, and durability of RCC members, thereby compromising their structural integrity and serviceability. The extent of degradation depends on factors such as maximum temperature, duration of heating, heating rate, cooling method, concrete composition, moisture content, and reinforcement characteristics.

6.1 Compressive Strength

Compressive strength is the most important mechanical property of concrete and serves as the primary parameter for structural design. Under elevated temperatures, concrete undergoes progressive strength reduction due to dehydration of calcium silicate hydrate (C-S-H) gel, decomposition of calcium hydroxide, and thermal expansion mismatch between aggregates and cement paste. Generally, concrete retains most of its original compressive strength up to approximately 200°C, with only minor reductions. Between 300°C and 500°C, strength decreases rapidly as micro cracks develop throughout the concrete matrix. At temperatures exceeding 600°C, severe deterioration occurs because of extensive cracking, increased porosity, and decomposition of hydration products. Beyond 800°C, concrete may lose more than half of its original compressive strength, resulting in significant reductions in load-bearing capacity and increased risk of structural failure.

6.2 Tensile Strength

Concrete possesses relatively low tensile strength compared with its compressive strength and is therefore more susceptible to thermal damage. Elevated temperatures accelerate crack initiation and propagation within the cement paste and interfacial transition zone (ITZ), causing a rapid decline in tensile resistance. Moisture evaporation and differential thermal expansion between aggregates and cement paste further intensify internal stresses, leading to crack widening and bond deterioration. Experimental studies have shown that tensile strength decreases more rapidly than compressive strength during fire exposure, making RCC members increasingly vulnerable to cracking, spalling, and serviceability problems. The loss of tensile capacity also reduces the effectiveness of the composite action between concrete and reinforcing steel.

6.3 Flexural Strength

Flexural strength represents the ability of concrete to resist bending stresses and is particularly important for beams, slabs, and bridge decks. Elevated temperatures significantly reduce flexural capacity by lowering both the tensile strength of concrete and the bond between concrete and reinforcement. Thermal gradients across structural members induce additional bending stresses and increase deflection. As cracks propagate under combined thermal and mechanical loading, the flexural stiffness of RCC members decreases considerably. Consequently, beams and slabs subjected to fire may experience excessive sagging, larger crack widths, and reduced moment-carrying capacity, even before compressive failure occurs.

6.4 Elastic Modulus

The modulus of elasticity is a measure of the stiffness of concrete and determines its resistance to deformation under applied loads. Among all mechanical properties, the elastic modulus is one of the most temperature-sensitive parameters. Even at moderate temperatures, significant reductions in stiffness occur because of microcrack formation, dehydration of hydration products, and degradation of the cement matrix. As temperature rises, the elastic modulus decreases continuously, resulting in greater deformation under identical loading conditions. The reduction in stiffness contributes to increased deflection, redistribution of internal forces, and reduced structural stability. Reinforcing steel also experiences a gradual decrease in elastic modulus at elevated temperatures, further weakening the overall rigidity of RCC members.

6.5 Bond Strength

Bond strength between concrete and reinforcing steel is essential for effective stress transfer and composite structural action. During fire exposure, differential thermal expansion, cracking, and deterioration of the interfacial transition zone reduce the adhesion and mechanical interlocking between concrete and steel. Elevated temperatures also weaken the rib-bearing mechanism of reinforcing bars, leading to bond slip and reduced anchorage capacity. As bond strength decreases, reinforcement becomes less effective in resisting tensile forces, increasing the possibility of premature cracking and structural failure. Adequate concrete cover and the incorporation of fibres are often recommended to improve bond retention under fire conditions.

6.6 Residual Strength after Cooling

The residual strength of RCC after cooling is a critical parameter for evaluating the post-fire serviceability and rehabilitation potential of damaged structures. Although some thermal strains recover during cooling, most chemical and microstructural damage remains irreversible. Rapid cooling, such as water quenching, often induces severe thermal shock, producing additional cracking and greater strength loss than gradual air cooling. Residual compressive strength, tensile strength, stiffness, and bond capacity depend on the peak temperature reached and the cooling regime adopted. Comprehensive post-fire assessment involving visual inspection, non-destructive testing, and laboratory evaluation is therefore necessary before deciding whether an RCC structure can be repaired, strengthened, or demolished. Understanding the degradation of mechanical properties under elevated temperatures is fundamental for developing reliable fire-resistant designs and effective rehabilitation strategies for reinforced concrete infrastructure.

VII. BEHAVIOUR OF REINFORCING STEEL AT ELEVATED TEMPERATURES

Reinforcing steel is a vital component of reinforced cement concrete (RCC), providing the tensile strength and ductility that concrete alone cannot offer. Under normal service conditions, steel reinforcement and concrete work together as a composite material because of their compatible thermal expansion characteristics and strong bond. However, exposure to elevated temperatures during fire significantly alters the mechanical and physical properties of reinforcing steel. As temperature increases, reinforcing steel undergoes reductions in yield strength, elastic modulus, and bond strength, while also exhibiting thermal creep and permanent deformation. These changes adversely affect the structural performance, stability, and fire resistance of RCC members. The extent of degradation depends on the maximum temperature reached, duration of heating, steel grade, cooling method, and fire exposure conditions.

7.1 Yield Strength Reduction

Yield strength is one of the most critical mechanical properties of reinforcing steel, representing the stress at which permanent plastic deformation begins. During fire exposure, the yield strength of reinforcing steel decreases progressively with increasing temperature due to changes in its microstructure. Up to approximately 300°C, the reduction in yield strength is relatively small, allowing the reinforcement to retain most of its load-carrying capacity. However, between 400°C and 600°C, the degradation becomes more pronounced as the steel experiences softening and loss of crystalline stability. At temperatures above 600°C, reinforcing steel may lose a substantial portion of its original yield strength, resulting in reduced resistance to tensile forces and increased susceptibility to excessive deformation. At temperatures approaching 800°C, the residual strength becomes insufficient to sustain design loads, greatly increasing the likelihood of structural failure. Consequently, the reduction in yield strength is a major factor influencing the fire resistance of reinforced concrete structures.

7.2 Modulus Degradation

The modulus of elasticity, commonly referred to as Young's modulus, determines the stiffness of reinforcing steel and its ability to resist deformation under applied loads. Elevated temperatures cause a continuous decrease in the elastic modulus because atomic vibrations increase and the bonding forces within the steel lattice weaken. As stiffness decreases, reinforcing bars undergo larger elastic and plastic deformations under the same loading conditions. This reduction in rigidity contributes to increased deflection of beams and slabs, larger lateral displacements in columns, and redistribution of internal forces throughout the structural system. The degradation of the elastic modulus also reduces the effectiveness of composite action between steel and concrete, resulting in lower structural stiffness and diminished load-bearing capacity during fire exposure.

7.3 Thermal Creep

Thermal creep is the time-dependent deformation of reinforcing steel under sustained loading at elevated temperatures. Unlike ordinary elastic deformation, thermal creep continues to increase as long as high temperatures and mechanical loads persist. During prolonged fire exposure, reinforcing steel experiences gradual elongation even when the applied stress remains constant. The rate of thermal creep depends on temperature, stress level, duration of exposure, and material composition. High temperatures accelerate atomic diffusion within the steel, allowing permanent deformation to accumulate over time. Thermal creep contributes significantly to excessive deflection, increased strain, and redistribution of stresses in reinforced concrete members. In severe fire conditions, the combined effects of thermal creep and strength degradation may lead to premature instability and structural collapse, particularly in heavily loaded columns and long-span beams.

7.4 Bond Deterioration

The structural efficiency of RCC depends on the effective bond between reinforcing steel and surrounding concrete. This bond ensures proper transfer of tensile and compressive forces and enables the two materials to behave as a single composite unit. Elevated temperatures adversely affect bond strength through several mechanisms, including differential thermal expansion, concrete cracking, dehydration of the cement matrix, and degradation of the interfacial transition zone (ITZ). As concrete loses strength and develops extensive microcracks, the mechanical interlocking between reinforcing bars and concrete weakens considerably. Rib-bearing resistance decreases, resulting in bond slip, reduced anchorage capacity, and ineffective stress transfer. Severe fire exposure may also cause concrete spalling, exposing reinforcement directly to flames and accelerating temperature rise within the steel. Consequently, bond deterioration not only reduces structural capacity but also compromises ductility, crack control, and overall fire performance. To improve bond retention under high-temperature conditions, adequate concrete cover, proper reinforcement detailing, fibre-reinforced concrete, and fire-protective coatings are commonly recommended.

VIII. FACTORS INFLUENCING THERMAL DEGRADATION OF REINFORCED CEMENT CONCRETE

The thermal degradation of reinforced cement concrete (RCC) is a complex phenomenon governed by the interaction of material properties, environmental conditions, and fire exposure characteristics. When RCC structures are subjected to elevated temperatures, their mechanical and thermo-physical properties progressively deteriorate due to dehydration of cement hydration products, thermal expansion, moisture migration, micro cracking, and degradation of the bond between concrete and reinforcing steel. However, the extent of this deterioration is not uniform and depends on several influencing factors. Understanding these factors is essential for accurately predicting the fire performance, residual strength, and serviceability of reinforced concrete structures.

8.1 Heating Rate

The heating rate refers to the speed at which the temperature of a concrete member increases during fire exposure. It significantly influences the thermal behaviour and degradation of RCC. A rapid heating rate produces steep temperature gradients between the surface and the interior of the concrete, resulting in differential thermal expansion and the development of high internal stresses. Rapid heating also accelerates moisture evaporation, causing the build-up of pore pressure within the concrete matrix. If the vapour pressure exceeds the tensile strength of concrete, explosive spalling may occur, exposing the reinforcing steel directly to fire. Conversely, slow heating allows heat to penetrate more uniformly throughout the concrete, reducing thermal gradients and enabling gradual moisture migration. Consequently, the severity of thermal damage generally increases with higher heating rates, making heating rate a critical parameter in fire-resistance assessment.

8.2 Maximum Temperature

The maximum temperature attained during fire exposure is the most influential factor affecting the mechanical and microstructural degradation of RCC. At temperatures below approximately 200°C, concrete experiences only minor changes, with limited strength reduction. Between 300°C and 500°C, dehydration of calcium silicate hydrate (C-S-H) gel and decomposition of calcium hydroxide begin, leading to microcrack formation and noticeable reductions in compressive strength, tensile strength, and stiffness. Beyond 600°C, extensive decomposition of hydration products, aggregate instability, increased porosity, and severe cracking substantially reduce the structural capacity of concrete. Reinforcing steel also loses yield strength and elastic modulus as temperature rises, further weakening the composite action within RCC members. Therefore, higher peak temperatures generally result in greater irreversible damage and lower residual structural performance.

8.3 Cooling Method

The method adopted for cooling fire-exposed RCC members has a significant influence on their residual mechanical properties. Natural air cooling allows gradual temperature reduction, minimizing thermal shock and reducing the likelihood of additional cracking. In contrast, rapid cooling through water quenching generates severe thermal gradients between the hot interior and the cooled surface, producing tensile stresses that may induce extensive cracking and spalling. Although water cooling is often necessary during firefighting operations, it can accelerate deterioration of concrete and reinforcement by increasing thermal shock. Consequently, RCC members subjected to sudden cooling usually exhibit lower residual strength and greater microstructural damage than those allowed to cool naturally.

Therefore, the cooling regime should always be considered during post-fire structural assessment.

8.4 Concrete Grade

Concrete grade significantly influences the fire resistance and thermal degradation characteristics of RCC. High-strength concrete possesses a denser microstructure and lower permeability than normal-strength concrete, resulting in higher compressive strength under ambient conditions. However, its low permeability restricts the escape of water vapour during heating, increasing pore pressure and making it more susceptible to explosive spalling. Normal-strength concrete, owing to its comparatively porous structure, permits easier moisture migration and often demonstrates better fire performance despite its lower initial strength. The selection of an appropriate concrete grade should therefore consider both mechanical requirements and anticipated fire exposure conditions.

8.5 Moisture Content

Moisture content is another important factor affecting the thermal degradation of RCC. Concrete with high moisture content experiences greater vapour pressure development during heating as water evaporates and becomes trapped within the pore structure. This increase in internal pressure promotes cracking and explosive spalling, particularly in dense, high-strength concrete. In contrast, partially dried concrete generally exhibits improved fire resistance because less moisture is available to generate vapour pressure. Nevertheless, prolonged drying before service may increase shrinkage and microcracking. Hence, the initial moisture condition of concrete should be considered when evaluating its behaviour under elevated temperatures.

IX. CONCLUSION

Reinforced Cement Concrete (RCC) undergoes significant thermo-structural and mechanical degradation when exposed to elevated temperatures, leading to reductions in strength, stiffness, durability, and overall structural integrity. This review highlights that temperature-induced physical, chemical, and microstructural changes in concrete and reinforcing steel adversely affect the load-carrying capacity and serviceability of RCC members. Experimental studies, microstructural investigations, and numerical simulations consistently demonstrate that factors such as heating rate, maximum temperature, moisture content, aggregate type, and reinforcement significantly influence fire performance. The review also emphasizes the effectiveness of fibre reinforcement, advanced characterization techniques, and finite element modelling in improving the understanding and prediction of thermal behaviour. Despite substantial progress, challenges remain in accurately modelling coupled thermo-hygro-mechanical behaviour and evaluating the long-term performance of advanced concrete materials after fire exposure. Continued research will support the development of more resilient, sustainable, and fire-resistant RCC structures, thereby enhancing structural safety and post-fire rehabilitation practices.for theory, practice, or policy. Highlight the significance of your contribution and suggest areas for future work. Avoid repeating sentences from the abstract.

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