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Thermal Performance of Sustainable Concrete at Elevated Temperatures

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Abstract*— Concrete is a heterogeneous composite material composed primarily of cement, aggregates, and water, often enhanced with supplementary cementitious materials and chemical additives to meet specific strength and durability requirements. The performance of concrete under elevated temperature conditions is highly dependent on its composition, making the behaviour of different concrete types significantly variable during and after thermal exposure. Furthermore, post-fire properties are influenced by several factors, including heating rate, curing duration and method, cooling regime, and mix constituents. This paper presents a comprehensive review of the influence of concrete constituents on the behaviour of concrete subjected to elevated temperatures. The findings indicate that the incorporation of fibers can enhance the residual tensile capacity of concrete; however, it may also increase the susceptibility to spalling due to the development of internal stresses. Supplementary cementitious materials, such as metakaolin and silica fume, are observed to improve strength characteristics, with silica fume demonstrating the most significant enhancement. Additionally, materials such as fly ash and silica fume contribute to reduced permeability, improved workability, and increased compressive strength, particularly at moderate levels around 200 °C. In general, most concrete types exhibit a gradual reduction in strength up to approximately 400 °C, followed by a more pronounced deterioration at higher temperatures. Beyond 800 °C to 1000 °C, significant structural degradation and spalling occur, rendering the material incapable of sustaining load. The review highlights the critical need for further research and the development of design code provisions that explicitly account for the effects of different concrete constituents and emerging sustainable materials under elevated temperature conditions.

Keywords*— elevated temperature; constituents; residual properties; spalling; cracking; fibers

I. INTRODUCTION

Fire hazards remain a critical concern for civil engineering structures worldwide, posing significant risks to human life, infrastructure, and economic resources. The frequency of fire incidents has increased in recent decades due to rapid urbanization and the growing dependence on electrical systems. Structural elements are particularly vulnerable during the construction phase, primarily due to the use of combustible materials such as wooden formwork. However, completed structures are also susceptible to fire damage, as evidenced by numerous global incidents reported in countries such as Taiwan, Dubai, China, and Australia. In several cases, fire events have led to partial or total structural collapse, highlighting the necessity of understanding material behaviour under elevated temperatures.

Over the past two decades, substantial advancements in concrete technology have introduced innovative materials such as fiber-reinforced concrete, self-compacting concrete, and self-healing concrete. These developments aim to enhance mechanical performance, durability, and sustainability. However, their behaviour under fire exposure or elevated temperatures remains a subject of ongoing research. Concrete is inherently a heterogeneous material, and its response to high temperatures is influenced by its constituent materials, including aggregates, binders, and fibers.

Previous studies have demonstrated that the thermal performance of concrete is highly dependent on its composition. The type, size, and mineralogical characteristics of aggregates significantly influence residual strength and spalling behaviour. For instance, quartz-based aggregates are prone to thermal instability due to phase transformation at approximately 573 °C, leading to internal cracking, whereas aggregates such as diabase exhibit comparatively better thermal resistance. Similarly, binder materials such as silica fume and metakaolin affect pore structure and vapor pressure development, thereby influencing spalling tendencies. Fiber reinforcement, particularly steel fibers, has shown variable effectiveness depending on dosage and geometry.

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Despite extensive research, existing design codes such as ACI and Eurocode provisions primarily address normal-strength and high-strength concrete under fire conditions, offering limited guidance for modern sustainable concrete materials. These codes do not comprehensively account for variations in material composition, heating rates, or cooling regimes, all of which significantly affect post-fire performance.

Cooling conditions play a crucial role in determining the residual properties of concrete. Commonly studied cooling regimes include natural air cooling (inside or outside the furnace) and water quenching. While natural cooling simulates real fire scenarios without firefighting intervention, water cooling represents emergency response conditions. Literature consistently indicates that rapid cooling, particularly water quenching, can cause severe thermal shock, resulting in increased cracking and reduced mechanical performance.

In addition, different experimental approachesnamely stressed, unstressed, and residual testingare used to evaluate concrete behavior under elevated temperatures. Among these, residual testing is the most widely adopted due to its practicality and ability to simulate post-fire structural conditions. However, stressed testing provides a more realistic representation of in-service conditions, though it is less commonly performed due to experimental complexities.

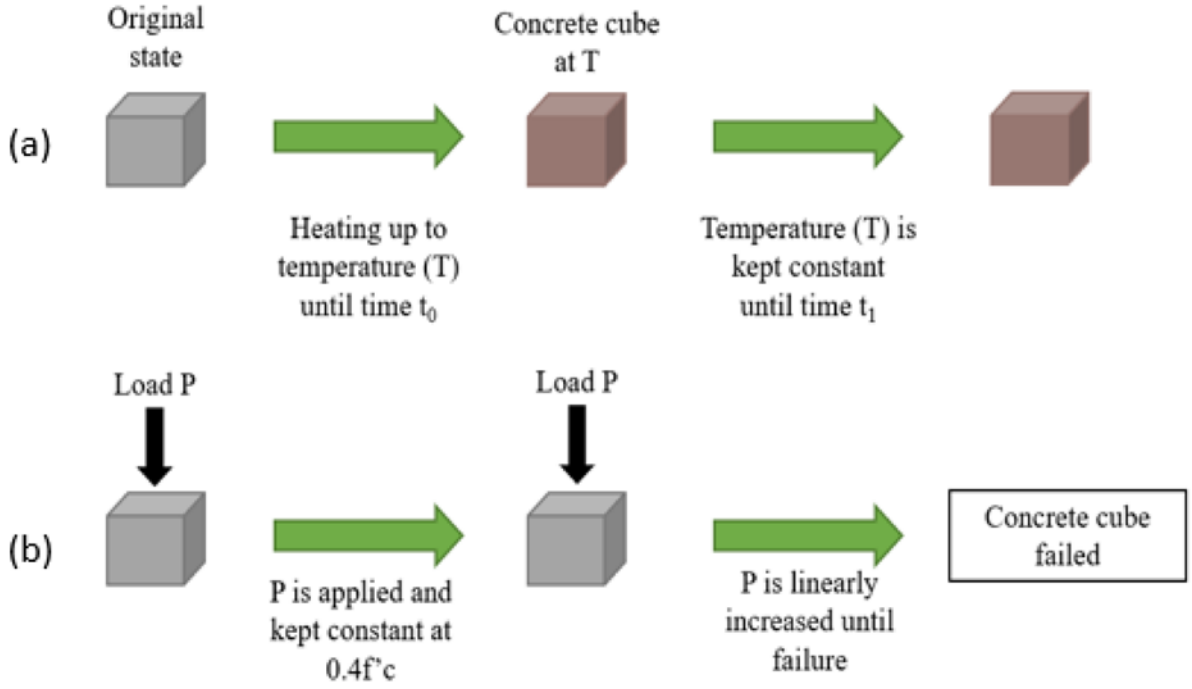


Fig. 1 (a) Heating and (b) loading schemes of the stressed condition.

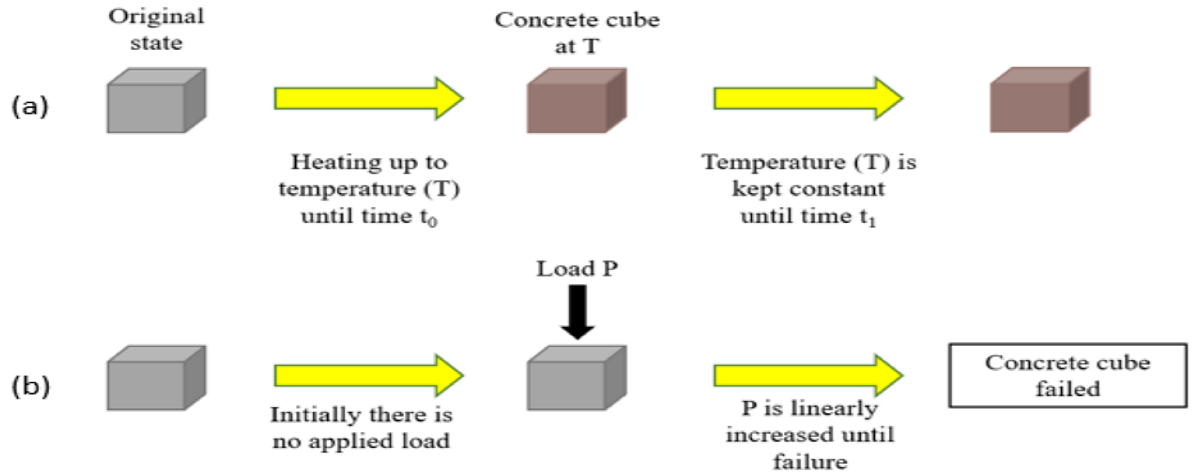


Fig. 2 (a) Heating and (b) loading schemes of the unstressed condition.

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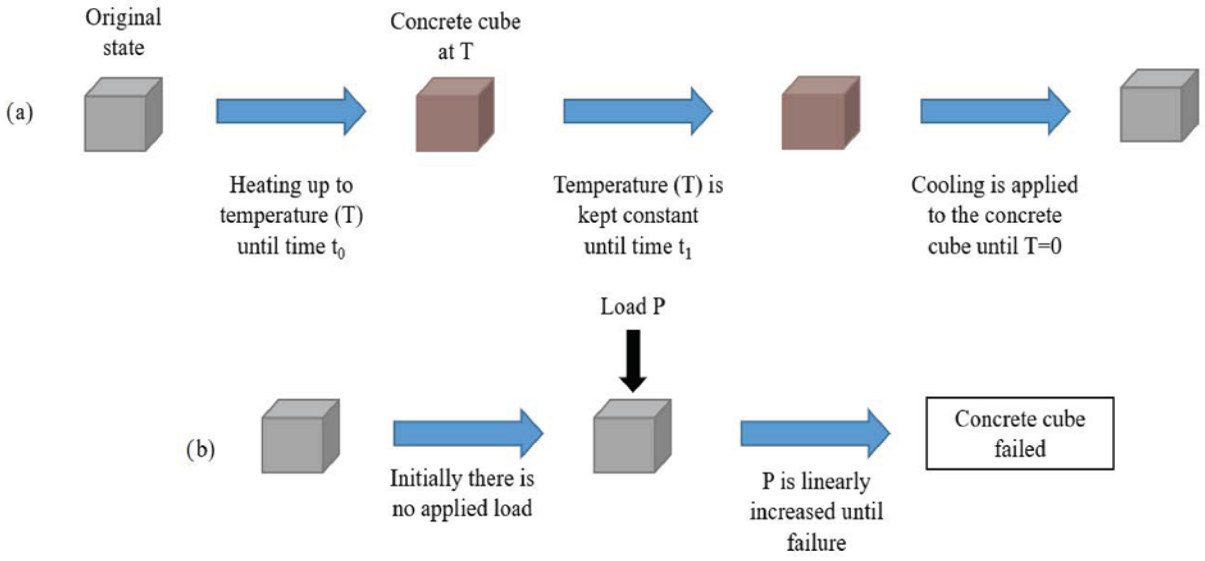


Fig. 3. (a) Heating and (b) loading schemes of the residual condition.

II. RESPONSE OF DIFFERENT CONCRETE TYPES UNDER ELEVATED TEMPERATURES

The behaviour of concrete at elevated temperatures is governed by a series of complex physical and chemical transformations. At the initial stages of heating, typically around 100 °C, concrete experiences a reduction in mass due to the evaporation of free water from its pore structure. Simultaneously, ettringite (3CaO·Al2O3·3CaSO4·32H2O)(3CaO·Al_2O_3·3CaSO_4·32H_2O)(3CaO·Al2O3·3CaSO4·32H2O) decomposes within the temperature range of 50 °C to 110 °C, contributing to early microstructural changes. As the temperature rises to approximately 200 °C, further mass loss occurs, and the mechanical response of concrete may either improve or deteriorate depending on its composition. Parameters such as water–cement ratio, cement type, and curing age significantly influence both free and chemically bound water content, thereby affecting thermal response.

Between 450 °C and 550 °C, the decomposition of portlandite (Ca(OH)2→CaO+H2O↑)(Ca(OH)_2 \→ CaO + H_2O↑)(Ca(OH)2→CaO+H2O↑) takes place, resulting in an endothermic reaction and substantial mass reduction. This dehydration process is widely recognized as a primary cause of strength degradation in concrete. At around 573 °C, quartz inversion occurs, leading to a volumetric expansion of approximately 5–7%, which induces internal stresses and cracking. At higher temperatures, particularly beyond 700 °C, the decomposition of calcium silicate hydrate (C–S–H) gel further weakens the concrete matrix. Ultimately, within the range of 600 °C to 1200 °C, concrete loses most of its load-bearing capacity.

A. Normal Strength Concrete (NSC)

Normal Strength Concrete (NSC) is the most widely utilized material in construction due to its balanced mechanical properties, cost-effectiveness, and ease of production. Typically, NSC exhibits compressive strengths ranging from 20 MPa to 50–55 MPa, depending on design codes and material specifications. Its microstructure is moderately dense, falling between lightweight and ultra-high-performance concretes.

NSC mixtures can incorporate various aggregate types and supplementary cementitious materials (SCMs) such as silica fume, fly ash, and ground granulated blast furnace slag (GGBS). These pozzolanic materials react with calcium hydroxide produced during cement hydration to form additional cementitious compounds, enhancing durability and long-term performance. Furthermore, SCMs contribute to sustainability by reducing cement consumption and associated CO_2 emissions. It is estimated that the use of such materials can reduce emissions by approximately 12%, highlighting their environmental significance.

In addition to sustainability benefits, blended cement systems containing fly ash and slag have demonstrated improved thermal resistance and reduced susceptibility to spalling under elevated temperatures. Consequently, there is increasing research interest in evaluating the performance of NSC with alternative binders, particularly under fire exposure conditions.

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- *Effect of Natural Cooling Outside the Furnace*

The performance of NSC under elevated temperatures is highly dependent on its composition and cooling conditions. Variations in constituent proportions can significantly influence microstructure, strength retention, cracking behavior, and mass loss. Generally, compressive strength decreases with increasing temperature; however, some studies report temporary strength gains of up to 20–60% at moderate temperatures (around 200–300 °C). These improvements are often attributed to delayed pozzolanic reactions and additional formation of C–S–H gel, particularly in mixes containing silica fume.

For instance, replacing approximately 7% of cement with silica fume can enhance strength by up to 60% at 300 °C and maintain original strength levels even at 600 °C. Similarly, the incorporation of air-entraining agents (AEA) has been shown to improve performance by increasing porosity, which facilitates the release of internal vapor pressure and reduces the risk of explosive spalling. However, beyond 400 °C, the beneficial effects of increased porosity diminish due to significant mass loss and matrix degradation.

Mass loss is a critical factor influencing residual strength. Even a modest weight reduction of about 5–6% can result in a compressive strength decrease of approximately 20%. Additionally, the coefficient of thermal expansion, which depends on aggregate type and mix composition, plays a vital role in thermal stability. Concrete containing siliceous aggregates typically experiences greater strength loss compared to that with calcareous aggregates. This is primarily due to higher thermal conductivity and the occurrence of quartz phase transformation in siliceous aggregates, which induces internal cracking.

Conversely, calcareous aggregates exhibit better thermal stability, retaining up to approximately 76% of their original strength at high temperatures (around 835 °C), compared to about 66% for siliceous aggregates. Limited studies have also indicated that silica fume can enhance flexural strength at moderate temperatures by approximately 10%.

Comparisons between experimental results and design code provisions, such as those in ACI 216 and Eurocode, reveal significant variability. Existing codes often fail to accurately capture the diverse behavior of NSC with varying compositions, highlighting the need for more comprehensive models that account for material heterogeneity and thermal effects.



Fig. 4. Samples that spalled inside the oven.

B. High Strength Concrete (HSC)

High Strength Concrete (HSC) is characterized by enhanced mechanical properties, durability, and stiffness compared to Normal Strength Concrete (NSC). These improvements are primarily achieved through the incorporation of supplementary cementitious materials such as silica fume, metakaolin, and ground granulated blast furnace slag (GGBS), along with a reduced water–cement ratio. The resulting dense microstructure and refined pore system contribute to its superior strength and durability performance.

Under elevated temperature conditions, HSC generally exhibits improved performance compared to NSC during the initial stages of heating. Several studies report that HSC can outperform NSC across a range of तापमान exposures. However, its behavior remains highly variable and is influenced by factors such as heating rate, cooling regime, and material composition.

Despite its advantages, HSC is particularly susceptible to explosive spalling when exposed to high temperatures. This vulnerability is mainly attributed to its low permeability and dense matrix, which restrict the escape of vapor generated during heating. As a result, significant pore pressure develops within the concrete, with values reported to reach up to 8 MPa—exceeding the typical tensile strength of HSC. This internal pressure buildup can lead to sudden and severe material failure.

To mitigate spalling, several strategies have been explored. The use of limestone aggregates has been found to improve thermal stability and reduce shrinkage effects, thereby lowering the likelihood of spalling. Additionally, limiting the silica fume content to below approximately 10% by weight can increase permeability and facilitate pressure dissipation. The incorporation of polypropylene (PP) fibers has also proven effective; these fibers melt at relatively low temperatures, forming micro-channels that enhance permeability and allow vapor to escape.

Overall, the fire performance of HSC remains an active area of research. A comprehensive understanding of the influence of mix constituents and thermal conditions is essential to improve its post-fire behavior and ensure structural safety under fire exposure.

- *Effect of Natural Cooling Outside the Furnace*

Experimental investigations on HSC subjected to natural cooling have demonstrated a wide range of behaviors, largely dependent on mix composition. In many cases, HSC exhibits significant कमजोरी and susceptibility to spalling when exposed to temperatures up to 300 °C. This effect is particularly pronounced in mixes incorporating heavyweight aggregates such as magnetite. For instance, partial replacement of coarse aggregates with magnetite (around 50%) results in reduced strength due to increased internal pressure associated with the dense matrix. At higher replacement levels (75–100%), specimens often experience तत्काल spalling as a result of excessive internal stresses.

Conversely, the use of air-entraining admixtures (AEA) has shown considerable benefits. HSC specimens containing AEA have demonstrated the ability to retain up to approximately 80% of their original compressive strength at temperatures as high as 600 °C. The entrained air voids act as pressure-relief zones, reducing vapor pressure buildup and thermal stresses. However, the effectiveness of AEA depends on the overall mix design.

Studies also indicate that combining silica fume with AEA provides intermediate performance—better than silica fume alone but generally inferior to AEA-only mixes. This behavior may be attributed to the competing effects of increased density (due to silica fume) and enhanced permeability (due to AEA). In some cases, excessive internal pressure caused by silica fume has led to spalling at temperatures around 500 °C.

Another important observation is that HSC without coarse aggregates, often referred to as high-performance micro-concrete (HPMC), demonstrates improved resistance to elevated temperatures. Such mixes can retain up to 50% of their compressive strength at 800 °C. The absence of coarse aggregates reduces internal stress concentrations, although initial strength loss may occur at lower temperatures. Partial strength recovery observed around 200 °C is attributed to moisture loss and continued hydration reactions.

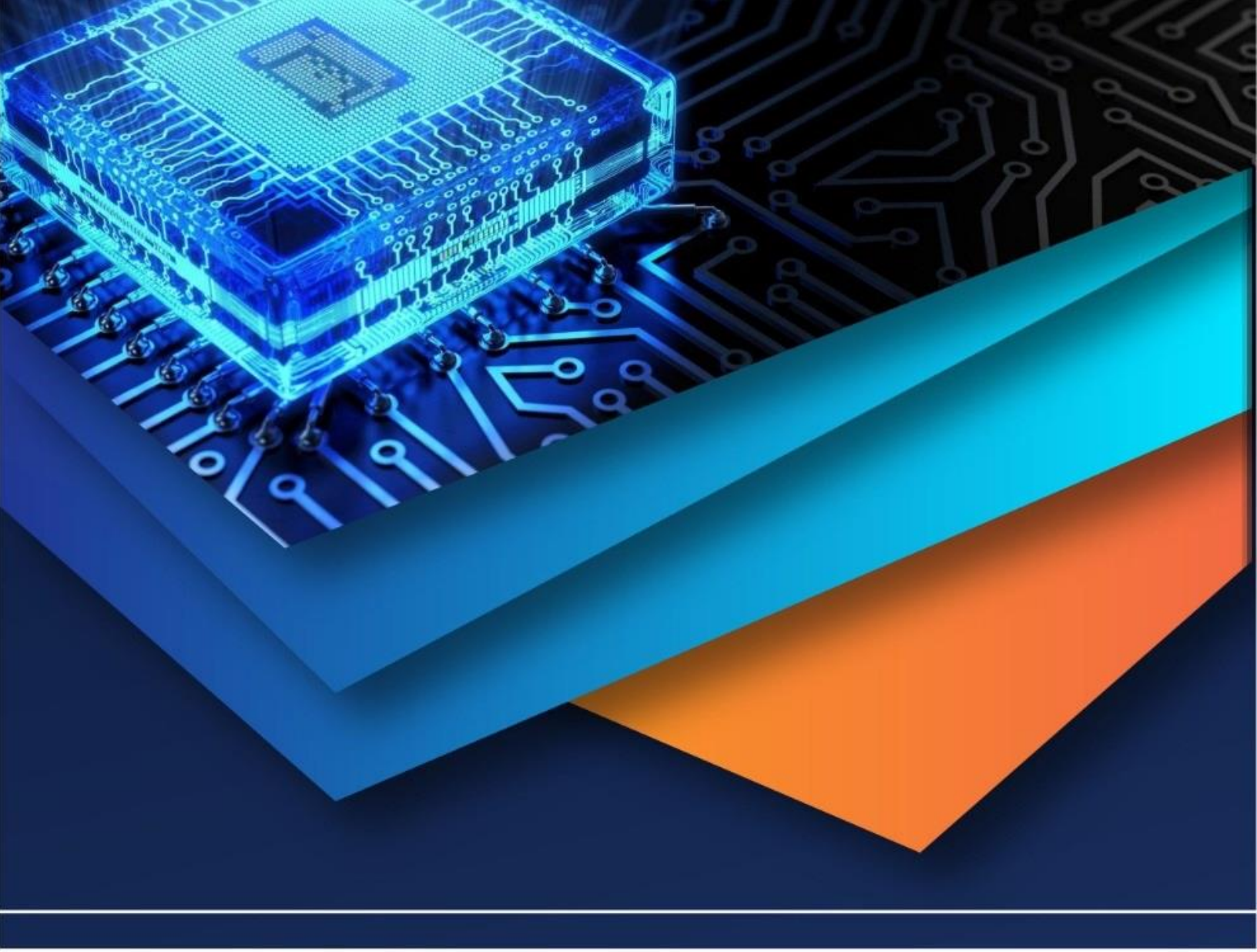
Additionally, certain HSC mixes exhibit temporary strength enhancement at moderate temperatures, which can be linked to the formation of additional calcium silicate hydrate (C–S–H) gel, improving the bond between constituents. Incorporation of materials such as metakaolin or ground pumice has also been shown to enhance thermal performance, with some mixes retaining up to 70% of their original strength at 500 °C. While metakaolin contributes to a denser matrix, it also helps mitigate deleterious reactions such as alkali–silica reaction, thereby improving durability under thermal loading.

Comparisons with standard design provisions, such as those in Eurocode, reveal significant discrepancies. Although Eurocode classifies HSC into different strength categories, experimental results often show considerable variation beyond these classifications. This highlights the strong influence of material composition on post-fire residual properties and underscores the need for more refined predictive models.

Furthermore, the inclusion of fibers, particularly polypropylene fibers, has been found to enhance both compressive and flexural performance after fire exposure by improving crack resistance and reducing spalling.

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