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Review of Post-Fire Mechanical Properties of M25 Concrete under Different Cooling Methods

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Abstract: The forensic evaluation of structural safety in fire-damaged reinforced concrete is a primary requirement for infrastructure disaster management. This comprehensive review focuses specifically on M25 grade concrete, defined by a 28-day characteristic compressive strength of 25 MPa, which serves as the structural standard for most residential and secondary commercial buildings globally. When internal temperatures rise above the 300–400°C threshold, the cementitious matrix undergoes permanent physical and chemical degradation, characterized by the dehydration of calcium silicate hydrate (C-S-H) and the $\alpha \rightarrow \beta$***quartz transformation in aggregates at 573°C. This review synthesizes empirical findings to highlight that the subsequent cooling method is as critical as the peak temperature reached. Data indicates that rapid water quenching induces severe thermal shock, which can reduce residual compressive strength by an additional 30–40% (approximately 38%) compared to gradual air cooling. At 600°C, M25 concrete typically loses about 50% of its initial compressive strength, reaching near-total structural failure at 800°C. This paper provides an in-depth analysis of mechanical property attenuation, elastic modulus (E) degradation, and microstructural forensic markers, offering evidence-based engineering benchmarks for post-fire assessment and rehabilitation.***

Keywords: Fire-damaged concrete, Residual mechanical properties, Elevated temperature, Cooling regimes, Thermal degradation, M25 concrete, Post-fire assessment

Nomenclature

- C-S-H: Calcium silicate hydrate
- CH: Calcium hydroxide (Portlandite)
- fck: Characteristic compressive strength (25 MPa for M25 concrete)
- E: Elastic modulus
- ITZ: Interfacial transition zone
- NSC: Normal strength concrete
- UPV: Ultrasonic pulse velocity
- $\alpha \rightarrow \beta$: Quartz phase transformation

I. INTRODUCTION

Determining whether a reinforced concrete frame remains stable enough for repair or requires complete demolition is the most immediate task for forensic teams after a fire incident (Garlock et al., 2012; Yaragal et al., 2012). Concrete is traditionally valued for its fire endurance, primarily due to its non-combustible constituents and low thermal diffusivity, which retard heat penetration into the core of structural members (Kodur and Naser, 2020; Barman et al., 2025).

The thermal conductivity of standard concrete typically ranges from 1.4 to 3.6 W/m·K at room temperature, dropping significantly to approximately 0.5–1.5 W/m·K once temperatures exceed 400°C (Barman et al., 2025). However, at elevated temperatures, the chemical bonds that provide structural integrity begin to deteriorate. M25 grade concrete starts to exhibit permanent chemical and structural disintegration when internal temperatures exceed 300–400°C (Agrawal and Kodur, 2020; Bindu Sai and Reddy, 2023).

Significantly, the damage observed after fire exposure is not solely governed by the peak temperature attained; the cooling methodology adopted plays an equally critical role (Botte and Caspeele, 2017; Yaragal et al., 2012). Sudden water quenching, commonly encountered during firefighting operations, generates steep thermal gradients between the outer surface and the inner core of concrete members. This results in the development of internal stresses that induce macro-cracking, spalling, and loss of bond strength, often causing more severe deterioration than thermal exposure alone (Janotka and Nürnbergerová, 2005).

This review establishes a correlation between cooling-induced thermal shock effects and microstructural degradation, thereby providing practical engineering thresholds and insights for evaluating the post-fire performance of M25 grade concrete.

II. METHODOLOGY OF LITERATURE REVIEW

This review was conducted through a systematic synthesis of peer-reviewed experimental studies and technical reports published between 2000 and 2025. A total of approximately 60 relevant research articles were critically analyzed to evaluate the post-fire mechanical behavior of normal strength concrete, with particular emphasis on M25 grade concrete.

A. *Databases and Search Strategy*

The primary databases utilized for this review include Scopus, Google Scholar, and ResearchGate. The search strategy involved the use of targeted keyword combinations such as “M25 concrete fire resistance,” “residual mechanical properties,” “water quenching thermal shock,” and “post-fire microstructural analysis” (Adamu et al., 2024).

B. *Selection Criteria*

The studies included in this review were selected based on the following criteria:

1) Focus on Normal Strength Concrete (NSC) with characteristic compressive strengths in the range of 20–30 MPa (including M25 grade concrete).
2) Availability of experimental data comparing different cooling regimes, including air cooling, furnace cooling, and water quenching.
3) Thermal exposure levels reaching a minimum of 400°C, with most studies extending up to 800°C.
4) Use of advanced diagnostic techniques such as Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), or Non-Destructive Testing (NDT) methods like Ultrasonic Pulse Velocity (UPV) and rebound hammer tests.

III. PHYSICOCHEMICAL TRANSFORMATIONS AND THERMAL THRESHOLDS

Concrete is a heterogeneous composite material in which the cement paste (binder) and aggregates respond differently to elevated temperatures, often resulting in incompatible thermal strains and internal stress development (Ahmad et al., 2022; Malik et al., 2020).

A. *Progressive Dehydration and Bonding Failure*

As M25 concrete is exposed to temperatures ranging from 100°C to 200°C, it loses free capillary moisture, and ettringite crystals begin to decompose (Agrawal and Kodur, 2020; Janotka and Nürnbergerová, 2005). Structural integrity remains largely unaffected up to approximately 300°C, beyond which the calcium silicate hydrate (C-S-H) gel starts to release its chemically bound water, leading to the initiation of strength degradation (Hager, 2013).

The critical mineralogical transformation in M25 concrete occurs between 400°C and 600°C (Dwaikat and Kodur, 2009; Gebre et al., 2024). Within this temperature range, Portlandite ($Ca(OH)_2$) decomposes into calcium oxide (CaO) and water vapor, as represented by the following reaction:

$$Ca(OH)_2 \rightarrow CaO + H_2O$$

This decomposition results in a significant increase in matrix porosity and a reduction in alkalinity, which adversely affects the passive layer protecting reinforcing steel against corrosion (Dwaikat and Kodur, 2009; Gebre et al., 2024).

Beyond 600°C, the C-S-H gel structure undergoes complete breakdown, leading to severe loss of cohesion and mechanical integrity. At this stage, the concrete becomes highly porous, brittle, and structurally unstable, rendering it unsuitable for load-bearing applications (Botte and Caspeele, 2017).

B. *Aggregate Behavior and Quartz Inversion*

M25 concrete mixtures typically incorporate siliceous aggregates containing quartz (Ahmad et al., 2022). At approximately **573°C**, quartz undergoes a reversible $\alpha \rightarrow \beta$ phase transformation, which is accompanied by a sudden volumetric expansion (Yaragal et al., 2012).

This abrupt expansion of aggregate particles, combined with the simultaneous shrinkage of the surrounding cement paste due to dehydration, generates significant internal tensile stresses within the concrete matrix. These stresses are particularly concentrated at the Interfacial Transition Zone (ITZ), which is inherently the weakest region in concrete (Malik et al., 2020).

As a result, microcracks initiate and propagate along the ITZ, leading to loss of bond strength between aggregates and cement paste. At higher temperatures (above 600°C), these microcracks coalesce into macrocracks, contributing to severe deterioration, reduction in mechanical strength, and increased susceptibility to spalling.

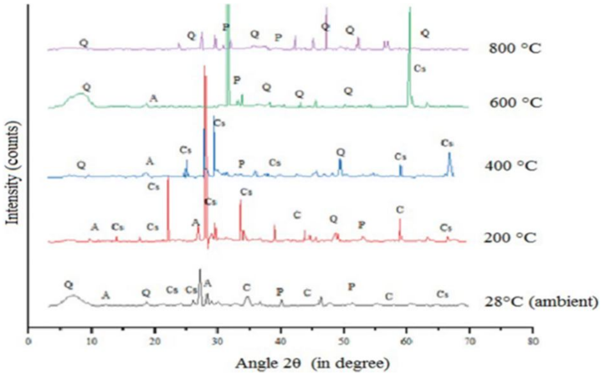


Figure 1: XRD diffractogram for M25 concrete exposed to different temperatures
(Source: Sureshbabu and Mathew, 2020).

IV. COMPARATIVE ANALYSIS OF COOLING REGIMES

The cooling method acts as a secondary thermal loading phase that significantly influences the residual properties of concrete after fire exposure (Botte and Caspeele, 2017).

A. Natural Air Cooling vs. Water Quenching

Air cooling allows concrete to return to thermal equilibrium at a relatively moderate rate, thereby minimizing the development of internal thermal gradients and associated stresses (Botte and Caspeele, 2017; Yaragal et al., 2012). Empirical studies indicate that air-cooled M25 concrete specimens retain approximately 15–20% more residual compressive strength compared to specimens subjected to water quenching (Bingöl and Gül, 2008). At around 400°C, air-cooled M25 concrete can maintain nearly 80% of its original compressive strength (Botte and Caspeele, 2017). In contrast, water quenching results in abrupt thermal contraction due to rapid cooling of the surface while the Internal core remains at elevated temperatures (Botte and Caspeele, 2017). This creates steep temperature gradients, leading to significant internal stresses, cracking, and potential spalling. Statistical meta-analyses confirm that, for M25 grade concrete, water quenching can cause an additional 30–40% reduction in residual compressive strength (approximately 38%) compared to gradual cooling methods (Botte and Caspeele, 2017; Chang et al., 2006).

Table 1. Residual compressive strength (%) of M25 concrete (fck = 25 MPa) under different cooling regimes.

Temperature (°C)	Furnace cooling (%)	Air cooling (%)	Water quenching (%)
200	100	97	90
400	97	80	70
600	67	57	45
800	54	46	39

(Data compiled from Yaragal et al., 2012; Botte and Caspeele, 2017).

B. Critical Analysis of Literature Contradictions

A significant divergence in the literature concerns the rehydration effect observed in fire-damaged concrete. While most studies (Botte and Caspeele, 2017; Yaragal et al., 2012) report that water quenching is detrimental due to the development of severe thermal gradients and associated cracking, some investigations (Ahmad et al., 2022) indicate that post-fire immersion can partially restore strength.

Specifically, it has been reported that specimens submerged in water for approximately 24 hours after thermal exposure may recover up to 70–75% of their original compressive strength, attributed to the rehydration of unreacted cement clinkers and partially dehydrated hydration products.

This apparent contradiction can be explained by distinguishing between rapid water quenching (spraying) and controlled post-fire immersion. Rapid quenching induces thermal shock, leading to microcracking and strength degradation, whereas prolonged immersion facilitates gradual rehydration and partial microstructural recovery.

Furthermore, the type of aggregate plays a crucial role in determining post-fire performance. Concrete incorporating river gravel aggregates generally exhibits greater strength degradation compared to limestone aggregates, due to the higher thermal expansion coefficient and quartz content in siliceous aggregates (Yaragal et al., 2012). This difference intensifies internal stresses and cracking under elevated temperatures.

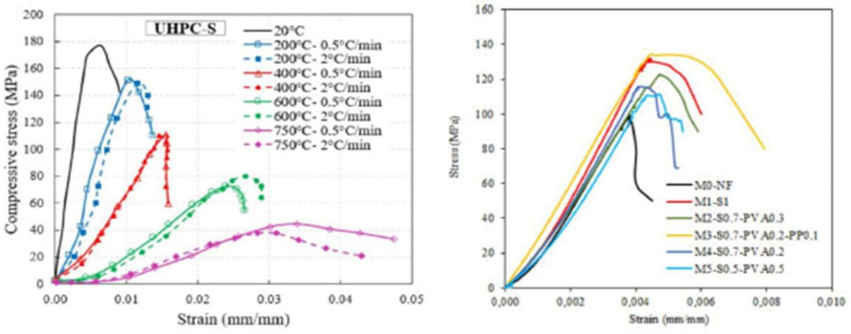
V. MECHANICAL PROPERTY ATTENUATION

A. Compressive and Tensile Sensitivity

Tensile properties of concrete are significantly more sensitive to elevated temperatures than compressive strength (Gebre et al., 2024). While the compressive strength of M25 concrete reduces to approximately 50% of its original value at around 600°C, the split tensile strength exhibits a much sharper decline.

Experimental studies indicate that split tensile strength can decrease by nearly 50% at temperatures as low as 300–400°C (Yaragal et al., 2012). This early degradation is primarily due to the initiation and propagation of microcracks within the cement matrix and along the Interfacial Transition Zone (ITZ).

At higher temperatures, the deterioration becomes more severe. By 800°C, the residual tensile strength of water-quenched M25 concrete reduces to approximately 5–10% (around 6%) of its original ambient value (Yaragal et al., 2012). This drastic reduction highlights the vulnerability of tensile properties to both thermal exposure and rapid cooling effects.



(a) **(b)**

Figure 2: Stress-strain relationship of concrete at room temperature and after exposure to 800°C
(Source: Ahmad et al., 2022).

B. Modulus of Elasticity (E) and Stiffness

The modulus of elasticity (E), which represents the stiffness of concrete, degrades more rapidly than other mechanical properties in normal strength concrete (NSC) when exposed to elevated temperatures (Hager, 2013).

At a peak temperature of approximately 400°C, M25 concrete specimens can lose up to 25–30% (about 28%) of their initial elastic modulus (E) (Savva et al., 2005). This reduction is primarily attributed to the onset of microcracking and the gradual decomposition of hydration products within the cement matrix.

At higher temperatures, the degradation becomes significantly more pronounced. By 600°C, the elastic modulus (E) is often reduced to less than 25% of its original ambient value (E_0) due to extensive matrix coarsening, increased porosity, and loss of inter-particle bonding (Malik et al., 2020; Hachemi et al., 2015).

This substantial reduction in stiffness indicates that even when some compressive strength is retained, the structural rigidity of concrete is severely compromised, leading to increased deformation under load and reduced serviceability.

VI. MICROSTRUCTURAL FORENSIC INDICATORS

A. SEM and Matrix Coarsening

Scanning Electron Microscopy (SEM) analysis of M25 concrete exposed to temperatures above 400–500°C reveals significant matrix coarsening due to the dehydration of Portlandite ($Ca(OH)_2$), which results in the formation of characteristic hexagonal voids within the cement matrix (Fernandes et al., 2017).

At these elevated temperatures, the breakdown of hydration products leads to increased porosity and loss of cohesion within the microstructure. The Interfacial Transition Zone (ITZ), being the weakest region in concrete, becomes highly susceptible to damage.

Water-cooled (quenched) specimens exhibit more severe microstructural deterioration compared to air-cooled specimens. SEM images typically show fragmented ITZ regions, widened microcracks, and discontinuities in the cement matrix, confirming the detrimental effects of rapid thermal contraction and thermal shock (Malik et al., 2020).

These microstructural changes directly correlate with the observed reduction in mechanical properties, particularly tensile strength and elastic modulus.

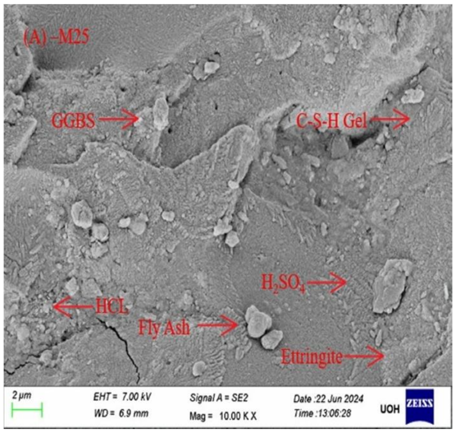


Figure 3: SEM image of M25 grade concrete after thermal exposure (Source: Narendra Kumar et al., 2024).

B. XRD Mineralogical Fingerprinting

X-ray diffraction (XRD) analysis enables the identification of mineralogical changes in concrete subjected to elevated temperatures. The disappearance of the Portlandite ($Ca(OH)_2$) peak is typically observed between 400°C and 600°C, indicating progressive dehydration of hydration products (Fernandes et al., 2017; Malik et al., 2020).

At higher temperatures, the formation of Larnite (Ca_2SiO_4) above 700–800°C signifies the near-complete dissociation of calcium silicate hydrate (C-S-H) gel and the breakdown of the cement matrix. This transformation reflects irreversible chemical degradation and loss of binding capacity within the concrete.

These mineralogical changes detected through XRD analysis serve as critical forensic indicators for assessing the extent of fire damage and residual structural integrity of M25 concrete.

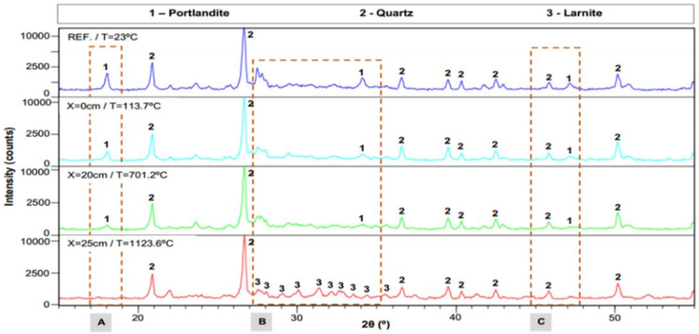


Figure 4: XRD diagrams showing mineralogical changes with depth in a fire-damaged member (Source: Fernandes et al., 2017).

VII. ENGINEERING IMPLICATIONS AND RECOVERY

If fire-damaged M25 concrete is re-exposed to a water-rich environment (re-curing), it can regain up to 70–75% of its pre-fire compressive strength (Kodur and Agrawal, 2017; Poon et al., 2001). This partial recovery is attributed to the rehydration of unreacted cement particles and the recombination of dehydrated hydration products, which contribute to microstructural densification. However, the extent of recovery is highly dependent on the peak temperature exposure and the severity of microcracking. In cases where structural members have experienced more than 30% loss in load-bearing capacity, strengthening or rehabilitation becomes necessary rather than relying solely on natural recovery.

Among the available repair techniques, ferrocement jacketing has proven to be an effective method for restoring structural performance. Experimental studies indicate that this technique can restore up to 75–80% of the original load-carrying capacity for concrete elements exposed to temperatures up to approximately 600°C (Arioz, 2007; Tabassum and Yeasmin, 2025).

These findings emphasize that post-fire assessment should not only consider residual strength but also incorporate appropriate rehabilitation strategies based on the extent of thermal damage.

VIII. CONCLUSION AND FUTURE SCOPE

A. *Summary of Findings and Decision Guidelines*

M25 grade concrete undergoes a critical structural threshold at approximately 600°C, where significant mineralogical decomposition and loss of mechanical integrity begin. This review confirms that natural air cooling is more effective in preserving residual structural capacity compared to rapid cooling methods. Water quenching induces severe thermal shock, resulting in an additional 30–40% (approximately 38%) reduction in compressive strength (Botte and Caspeele, 2017).

Engineering Recommendation: Concrete exposed to temperatures beyond 600°C, particularly when subjected to rapid cooling (water quenching), should be considered structurally compromised. In such cases, demolition or major rehabilitation should be preferred over reuse, unless detailed structural assessment proves otherwise.

B. *Engineering Implications*

A typical 25–40 mm concrete cover is insufficient to adequately protect reinforcing steel once surface temperatures exceed approximately 500–600°C (Sharma et al., 2025). At these temperatures, bond strength degradation and loss of alkalinity can accelerate reinforcement corrosion.

Therefore, engineers must prioritize Non-Destructive Testing (NDT) techniques such as Ultrasonic Pulse Velocity (UPV) and rebound hammer tests to evaluate the depth and severity of damage before recommending repair or strengthening measures.

C. *Future Research Directions*

Future research should focus on the incorporation of hybrid fiber systems (polypropylene and steel fibers) in M25 concrete to mitigate spalling, enhance thermal resistance, and improve post-fire ductility.

Additionally, there is a need to establish standardized guidelines for post-fire rehabilitation, particularly regarding:

- Optimal re-curing duration
- Reliable residual strength prediction models
- Performance-based repair strategies for fire-damaged structures

Such developments will contribute to safer, more economical, and scientifically informed decisions in post-fire structural assessment.

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