The Impact of High-Temperature Exposure from Fire on Concrete Quality: A Review and Experimental Plan

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ABSTRACT

Concrete is one of the most widely used materials in the construction of buildings, bridges, and infrastructure thanks to its compressive strength, durability, and relatively low production cost. However, its main weakness lies in its vulnerability to high temperatures. When exposed to fire, concrete can suffer significant quality degradation through both physical mechanisms (such as water evaporation, thermal cracking, and spalling) and chemical changes (like the decomposition of calcium hydroxide and damage to C-S-H gel). This study investigates how exposure to high temperatures up to 500°C affects the performance of low-strength concrete (f'c ≈ 12 MPa), with a particular focus on residual compressive strength and visible surface changes after a fire. The research combines a literature review with a planned laboratory experiment using cylindrical concrete specimens exposed to 200°C, 300°C, 400°C, and 500°C. Findings show that concrete remains relatively stable up to 200°C, with a strength reduction of less than 5%. Between 300°C and 400°C, strength drops significantly up to 28% and microcracks begin to form. At 500°C, concrete loses over 40% of its strength, accompanied by a noticeable color shift to whitish-gray and the appearance of wide cracks. These symptoms point to irreversible microstructural damage. This research is intended to support post-fire safety assessments, especially for buildings constructed with lower-grade concrete. The results confirm that exposure to around 500°C is sufficient to render a structure unsafe mirrored by the real-life case of a school fire in Penajam, where the building was ultimately demolished due to concrete degradation.

Keywords: compressive strength, concrete, fire, high temperature, low-strength concrete.

1. INTRODUCTION

Indonesia is currently facing a growing threat from building fires. According to data from Statistics Indonesia [1], the number of structural fire incidents including those involving offices, hospitals, and multi-story buildings has been rising by approximately 5% each year. This trend reflects an increasing frequency of fire cases in recent times. These incidents not only endanger lives but also result in substantial economic losses due to infrastructure damage. Once a fire is extinguished, a critical challenge remains: assessing whether the affected concrete structure is still safe and usable, or if it needs to be reinforced or in some cases, demolished altogether to ensure public safety.

Concrete is the most widely used material in construction, valued for its high compressive strength, durability, and relatively low cost. It is a composite material made of Portland cement, fine and coarse aggregates, water, and various additives. Despite its many strengths, concrete performs poorly when exposed to high temperatures [2], [3]. During extreme heat such as that encountered in a fire concrete can lose much of its quality and strength. The surface may become charred and discolored, and the structure's overall integrity may degrade significantly. Field studies have reported several forms of fire-induced damage in concrete, such as hairline cracks, spalling of the surface layer, brittleness, and even the fracturing of structural elements. These physical signs are strong indicators of a substantial reduction in concrete strength. Without a thorough post-fire assessment, a building that appears outwardly intact may conceal serious internal damage, posing a high risk of collapse or at the very least becoming unfit for continued use.

Recent experimental and review studies indicate that concrete begins to show notable degradation of stiffness and strength in the range of about 300–400°C, while damage becomes more severe at higher temperatures depending on moisture condition, heating rate, and aggregate type [2], [3]. For post-fire decision-making, assessment methods commonly combine visual inspection, destructive testing, nondestructive testing, and/or numerical modeling to estimate residual capacity and guide repair or demolition decisions [4]-[8].

However, it's important to note that most of these studies focus on high-strength concrete typically used in developed countries. In Indonesia, standard-strength concrete (f'c around 20–25 MPa) still dominates the construction sector. Currently, there is limited data available on how this type of concrete performs after fire exposure in the Indonesian context. That makes this study particularly important. By analyzing how fire affects the strength of the kinds of concrete commonly used in Indonesia, this research aims to provide deeper insights into post-fire strength reduction in standard-grade concrete. The findings are also expected to serve as a practical reference for evaluating the safety of fire-affected buildings in the country.

2. THEORY AND METHODS

Fundamentals of Concrete in Building Fires

Concrete building elements (slabs, beams, columns, walls, stair cores) consist of aggregates bound by hydrated cement paste and reinforced or prestressed steel. In compartment fires, gas temperatures rise quickly, often plateau during a fully developed phase, then decrease during cooling. Inside members, steep thermal gradients and moisture migration drive physical and chemical changes that reduce stiffness and strength, weaken bond, and may trigger spalling-ultimately threatening load-bearing capacity and overall robustness under continuity and restraint.

Key severity factors include: peak temperature, heating/cooling rate, duration of exposure, mechanical restraint and load level during heating, moisture condition, mix design and aggregate mineralogy, member thickness, and cover depth.

Temperature-Dependent Damage Mechanisms in Building Members

1. Hygral Effects (20–200 °C).
   Free water evaporates and bound water begins to migrate. In low-permeability, moist concrete subjected to rapid heating, pore pressure can build up, causing microcracking

and potentially explosive spalling at heated faces (e.g., soffits of slabs and beam undersides) [3], [9], [10].

2. Dehydration of Hydrates (≈105–400 °C).
   C–S–H, ettringite, and portlandite lose bound water. The matrix becomes less continuous, ITZ debonding increases, and stiffness tends to degrade earlier and faster than compressive strength [2], [3].
3. Chemical Decomposition (400–800 °C).
   a. Portlandite decomposes (400–600 °C), causing a marked drop in stiffness and strength [2], [3].
   b. C–S–H depolymerization intensifies beyond 600 °C, severely reducing cohesion [2].
   c. Aggregate transformations (e.g., α–β quartz transition 573 °C in siliceous aggregates; carbonate decarbonation at higher temperatures) introduce incompatibilities and additional cracking [2], [3].
4. Thermal Mismatch, Transient Creep, and Restraint.
   Different thermal expansion of paste, aggregates, and steel induces shear and tension at the ITZ. Under sustained gravity loads and structural restraint, transient thermal creep accelerates inelastic strains, amplifying deflections and damage [2], [3].
5. Spalling in Building Elements.
   Spalling arises from combined pore-pressure and thermal-stress mechanisms, and is promoted by dense/high-strength mixes, high moisture, thin covers, rapid heating, high axial load (columns/walls), and quenching. Spalling reduces effective section and removes protective cover from reinforcement, sharply increasing vulnerability. Mitigation approaches such as polypropylene fibers and pre-drying have been widely reported to reduce explosive spalling risk [9]-[13].

Resid**ual Properties Relevant to Building Safety**

1. Compressive Strength. Declines nonlinearly with temperature often modest up to 200 – 300 °C, then accelerating beyond 400 °C [2].
2. Elastic Modulus. Degrades faster than strength; serviceability (deflection, crack width) can govern even when residual strength seems acceptable [2].
3. Tensile/Flexural Strength. More temperature-sensitive, facilitating crack initiation and growth [2].
4. Bond to Reinforcement. Cover cracking/spalling, matrix softening, and thermal mismatch reduce bond and anchorage; slip at laps/anchors becomes critical [4].
5. Durability. Increased post-fire porosity accelerates carbonation and chloride ingress; if cover is lost, corrosion risk rises quickly [2].

Low-strength concretes (10-15 MPa) typical of older buildings may have higher initial porosity, which can lessen explosive spalling risk compared to very dense HSC. However, modulus and tensile capacity still deteriorate rapidly beyond 300-400 °C, making axially loaded columns and walls particularly sensitive [2], [9].

2.2 Methods

This study was initiated following a fire incident at SD Negeri 022 Penajam, located on Jenderal Sudirman Street, Penajam Paser Utara Regency, East Kalimantan, Indonesia. The fire broke out on Wednesday, January 31, 2024, around 4:00 PM local time, destroying five rooms including three classrooms, the teachers' lounge, and the principal's office. The post-fire condition of the school is shown in Figure 1, where significant damage can be seen in the roof and wall elements, indicating the intense impact of the flames.

To assess whether the building structure remained viable after the fire, a laboratory simulation was conducted alongside residual compressive strength testing of the concrete, which served as the basis for a technical evaluation.

Figure 1. Post-fire condition of SDN 022 Penajam on January 31, 2024, showing partial destruction of the school building (photo: field documentation)

Materials and Sample Preparation

Since it was not feasible to retrieve concrete samples directly from the fire-damaged building, new concrete specimens were produced in the laboratory using a mix design estimated to match the original structure’s concrete. The mix used was classified as low-strength normal concrete, with an estimated characteristic compressive strength of approximately 10–15 MPa comparable to Class I concrete. The mix consisted of Portland cement, fine aggregate (sand), coarse aggregate (gravel), and water. The proportions were designed specifically to achieve the desired low compressive strength, with a water-to-cement ratio of about 0.6.

The freshly mixed concrete was cast into cylindrical molds measuring 15 cm in diameter and 30 cm in height, which corresponds to standard specimen dimensions for compressive strength testing. Each cylinder was left in the mold for 24 hours to allow initial setting, then demolded and cured under moist conditions at room temperature until reaching the planned testing age of 28 days.

For this study, a total of 15 cylindrical specimens were prepared and divided into five treatment groups:

1. Control group (no heating): specimens stored at room temperature (~27°C) to serve as the baseline.
2. 200°C heating: specimens heated to 200°C.
3. 300°C heating: specimens heated to 300°C.
4. 400°C heating: specimens heated to 400°C.
5. 500°C heating: specimens heated to 500°C.

Each group consisted of three identical specimens, allowing for the calculation of average residual compressive strength under each condition. The number of samples and replications was selected to ensure the test results would be statistically representative.

High-Temperature Treatment (Fire Simulation)

After reaching the age of 28 days, the cylindrical concrete specimens assigned to the high-temperature treatment groups were heated in a laboratory furnace to simulate fire conditions. Heating was carried out gradually until the target temperatures were reached specifically, 200°C, 300°C, 400°C, or 500°C, depending on the treatment group. The heating rate was maintained at approximately 5°C per minute to prevent thermal shock or sudden damage to the concrete. Once the target temperature was achieved, it was held steady for around 2 hours to ensure that the entire volume of the specimen reached a uniform temperature.

The selected temperature range of 200–500°C reflects typical fire conditions observed in structural fires. A temperature of 200°C represents mild exposure, where concrete is not expected to show significant strength loss, while 500°C represents severe fire exposure, where substantial strength degradation can occur potentially reducing the residual strength of concrete to 75 - 80% of its original capacity.

Following the heating phase, the specimens were allowed to cool naturally in open air until their temperature returned to ambient conditions. This natural cooling method was chosen to closely simulate real-world post-fire scenarios, where structural elements cool down on their own without being quenched with water-avoiding thermal shock, which could worsen damage. Throughout the heating and cooling processes, visual changes in the concrete were carefully observed and documented. These included the appearance of hairline cracks on the surface and changes in color (e.g., turning whitish or grayish) as a result of heat exposure. These qualitative observations were valuable in complementing the compressive strength data and provided further insight into the extent of thermal damage.

Compressive Strength Testing

Once the specimens had cooled down and returned to room temperature after heat treatment, compressive strength testing was performed on each concrete cylinder. The tests were conducted using a hydraulic compression machine with a capacity of approximately 2000 kN, following the procedures outlined in the Indonesian Standard SNI 1974:2011 [14].

Each cylindrical specimen was positioned vertically between the loading plates of the machine, and a steadily increasing load at a rate of about 0.25 MPa per second was applied until the specimen failed. The maximum load at failure was recorded, and the compressive strength ($f'c$) was calculated by dividing this load by the cross-sectional area of the cylinder.

For each temperature treatment group, three residual strength values were obtained one from each specimen. These were then averaged to determine the mean residual compressive strength for that specific temperature. The entire testing procedure followed standardized methods to ensure the validity and scientific reliability of the results.

Data Analysis and Structural Feasibility Criteria

The residual compressive strength results from the various temperature treatments were analyzed to assess the extent to which heat exposure affected the concrete's strength. The average compressive strength at each temperature was compared to the average strength of the control group (unheated samples) to determine the percentage of strength loss due to thermal exposure.

These residual strength values were then evaluated against standard structural feasibility criteria. In general, if post-fire concrete retains a compressive strength above its original design strength and the reduction is no greater than 20–25% from the initial value, the structure is still considered serviceable possibly requiring only minor repair or reinforcement. However, if the strength loss is severe exceeding 50% of the original strength and the remaining strength falls below the required threshold to carry design loads, the structure is deemed unsafe for continued use.

In such cases, full structural retrofitting or even demolition is recommended, followed by reconstruction using new structural elements that meet safety standards. Based on these evaluation criteria, the residual compressive strength data provide a clear technical basis for determining whether the SDN 022 Penajam school building, after the fire, could still be reused or whether it should be demolished to ensure the safety of its occupants.

3. RESULTS AND DISCUSSION

Residual Compressive Strength Test Results

Compressive strength testing was conducted on low - strength concrete (f'c ≈12 MPa) after exposure to elevated temperatures of 200°C, 300°C, 400°C, and 500°C. The average results are summarized in Table 1.

Table 1. Residual Compressive Strength of Low-Strength Concrete after High Temperature Exposure

Temperature (°C)	Initial Strength (MPa)	Residual Strength (MPa)	Strength Loss (%)
25	12.5	12.5	-
200	12.5	11.9	4.8
300	12.5	10.8	13.6
400	12.5	9.0	28.0
500	12.5	7.2	42.4

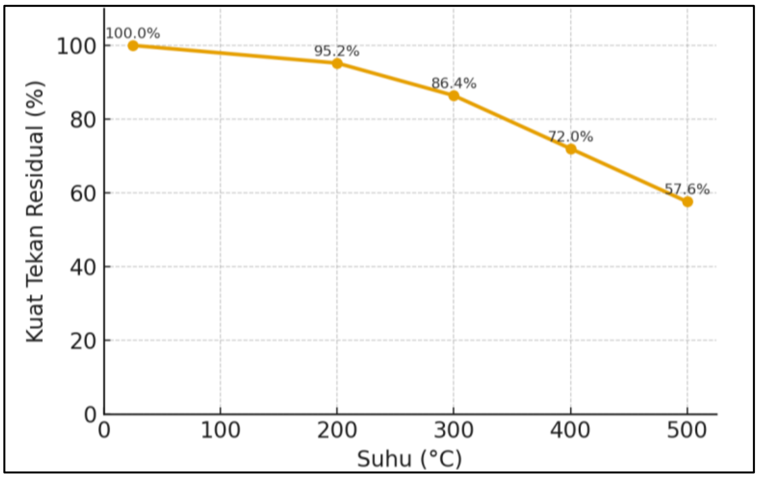

Figure 2. Graph of compressive strength loss in low-strength concrete due to high-temperature exposure

Figure 3. Illustration of color changes and surface condition of low-strength concrete after exposure to temperatures between 25°C and 500°C

Discussion

1. Low Temperature (≤200°C)

At 200°C, the strength reduction was still minimal around 5%. This was primarily due to the evaporation of free water from the concrete's pores, which did not significantly affect the chemical bonds within the matrix. Under these conditions, the concrete is still considered structurally sound and safe for continued use [2], [3].

2. 300°C Exposure

At 300°C, compressive strength dropped by approximately 13–15%. In this temperature range, partial dehydration of calcium hydroxide [$Ca(OH)_2$] begins, and microcracks start to form due to differences in thermal expansion between the cement paste and aggregates. Although the concrete still retains enough strength to bear loads, its long-term durability becomes questionable [2].

3. 400°C Exposure

The strength loss becomes more pronounced at around 28%. The damage is largely due to intensified decomposition of $Ca(OH)_2$, which is commonly reported to accelerate beyond ~400°C in normal concrete [2], [3]. In field observations, concrete subjected to this level of heat showed more visible cracking and discoloration, ranging from grayish tones to reddish hues depending on the type of aggregate used.

4. 500°C Exposure

At 500°C, low-strength concrete retained only about 57–60% of its original compressive strength. This level of degradation is consistent with datasets summarized in recent reviews [2] and with reduction factors provided in Eurocode 2 structural fire design (BS EN 1992-1-2:2004+A1:2019) [15]. While the structure may remain standing under these conditions, it is no longer safe for long-term use. Extensive microcracking, increased porosity, and a severe weakening of the bonds between cement paste particles compromise its structural integrity.

5. Implications for the SDN 022 Penajam Fire Incident

The case of the school fire in Penajam, which led to the demolition of the building, aligns well with the findings of this study. Concrete exposed to temperatures of up to 500°C had lost nearly half of its strength, and its microstructure had undergone irreversible degradation. Even if some elements appeared visually intact, they were structurally compromised. Hence, the decision to demolish the building was an appropriate and necessary step to ensure safety.

Based on the laboratory results, it is evident that high-temperature exposure up to 500°C has a significant impact on the compressive strength of low-grade concrete (f'c ≈12 MPa). While the concrete tends to remain stable at lower temperatures, there may be slight improvements or negligible changes up to around 100°C, likely due to pore water evaporation leading to matrix densification. Strength reduction becomes more noticeable above ~200°C, with losses of around 10 - 20% observed at that level. Some partial strength recovery may occur near 300°C, possibly due to steam redistribution and changes in pore structure, but once the temperature exceeds 300 - 400°C, the decline becomes more severe.

At the highest tested temperature range (400 - 500°C), the drop in strength was substantial. Microstructural damage becomes the dominant factor: the cement paste undergoes dehydration (with bound water evaporating and hydrated compounds like $Ca(OH)_2$ breaking down), and thermal expansion mismatch between the paste and aggregates leads to microcracking and a loss of internal cohesion. As a result, at around 500°C, the concrete retains only a fraction of its initial strength. Test results showed that residual strength ranged from approximately 40 - 60% of the original value meaning about half or more of the strength was lost, depending on the mix composition. These findings are consistent with other studies reporting similar strength loss in normal concrete exposed to 500 - 600°C [2], [11].

Visually and mechanically, fire-exposed specimens (≥400°C) displayed a different failure pattern compared to unexposed concrete. Numerous surface microcracks formed, and failure became more brittle specimens tended to break in a "soft," crumbling manner with cracks propagating widely indicating a weakened microstructure caused by heat exposure [2].

4. CONCLUSIONS

Practical implications: low-strength concrete exposed to temperatures around 500°C can suffer severe strength degradation, even if it doesn't appear completely damaged to the naked eye. In the context of building fires, this suggests that structural elements made from low-strength concrete may lose a significant portion of their load-bearing capacity after cooling. As such, post-fire structural evaluations are essential. Any elements exposed to high heat should undergo compressive strength testing or be replaced or retrofitted before being reused, considering their strength may be reduced by half or more.

Furthermore, these findings highlight the importance of implementing fire protection measures for concrete elements such as applying fire-resistant insulation layers or using concrete mixes with enhanced thermal resistance, particularly when structures are expected to operate in high-temperature environments. Overall, this study serves as a warning that high-temperature exposure causes permanent damage to concrete quality, and this factor must be carefully considered in the design and post-fire assessment of low-strength concrete structures.

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