

Original Article

Parametric Study on the Fire Resistance of Reinforced Concrete Slabs under ISO 834 Standard Fire Exposure

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Abstract - The design of reinforced concrete slabs needs to take into account fire protection, as extreme heat can damage both concrete and steel and can therefore compromise the structure's ability to support loads. This study addresses the impact of cover, thickness, and concrete compressive strength on the fire resistance of concrete slabs. The main goal of the study is to identify the important parameters and effective methods to improve fire resistance. The performance of a benchmark slab, which is simply supported and exposed to the ISO fire, was analysed. Models of strength deterioration were used to assess the concrete and steel reinforcements, and the bending strength deterioration was assessed. Results indicate that the fire resistance of the slab was increased by approximately 10 minutes by increasing the slab thickness from 180 mm to 220 mm, and the cover increased from 15 to 20 mm, with a significant 25-minute improvement. In contrast, all ranges of concrete compressive strength reached the limit of approximately 65 minutes, so no significant improvement was observed. The most significant improvement to fire resistance was observed with increased cover, followed by increased slab thickness, and little to no improvement was observed by increasing the compressive strength of concrete. These results provide practical guidance for the performance-based fire design of concrete slabs, emphasising targeted improvements in cover depth as an efficient means to enhance fire endurance.

Keywords - Reinforced concrete slab, Fire resistance, Concrete cover, Slab thickness, Bending strength degradation.

1. Introduction

Fire resistance has become an increasingly essential factor in structural design and is now included in various national and international codes and standards. Concrete has a natural fire resistance. However, when exposed to elevated temperatures, their mechanical properties, such as compressive strength, modulus of elasticity, and volume stability, are drastically diminished, which may eventually lead to unwanted structural failures [1-3]. Simultaneously, elevated temperatures damage the reinforcement by lowering its yield strength, resulting in excessive deflection and eventual failure of the structural member [4]. Vertical fire spread between floors can worsen fire-induced failures in multi-storey buildings by both speeding up structural collapse and hindering firefighting and rescue operations [5].

In this sense, slabs are important for compartmentalisation as they are the horizontal elements that limit the spreading of fires across the compartments of a building. Research shows that cover concrete consolidation improves the fire resistance of elements [6, 7]. However, for slabs most of which are designed to transmit live loads to the supporting framing (beam and column assembly), a larger thickness to achieve a higher fire rating increases the dead load

of the structure [8]. This renders the usual increased cover solution more difficult to implement for slabs than for other structural elements.

When concrete is exposed to a fire, several chemical and physical changes occur, including the loss of moisture, dehydration of the cement paste, and the disintegration of the aggregates. These changes happen because of the presence of high temperature changes, especially on the layers that are at the surface and exposed to the fire. Such changes can lead to the development of high compressive stress at the heated spots, resulting in localised spalling, which in turn exposes the concrete reinforcements to fire. When the reinforcements are exposed to fire, the yield strength of the reinforcements is affected negatively and quickly [9-11]. In addition, the concrete slab stiffness and the boundary restraint conditions are critical in the overall fire performance of concrete slabs because they influence the thermal deformation and the way the load is redistributed during the fire [12-14].

Considerable research has been conducted over the past few years on the structural behaviour of reinforced concrete slabs under high-temperature conditions [15-19]. All studies indicate that concrete durability decreases with increasing



temperature. This occurs because heat exposure causes concrete to undergo physical and chemical changes such as moisture loss, drying of the cement paste, and aggregate disintegration. In addition, water evaporation results in high pore pressures, which can lead to the formation of microcracks and degradation of the concrete material [20, 21].

The behaviour of simply supported composite slabs under elevated temperature conditions has been numerically investigated by Piloto et al. [22]. This study focused on the impact of load levels on the behaviour of concrete and steel deck connections. To simulate the behaviour of composite slabs, their model contained an air gap, and the slabs were tested under a constant external force. The study found that at constant load, vertical deflection increased at elevated temperatures, largely due to the temperature gradient and the development of tensile membrane behaviour. The results also showed that the air gap significantly altered the cross-sectional temperature field, which affected the overall thermal and structural response of the slab.

The yield strength of steel reinforcement decreases with increasing temperature, reducing the steel's load-bearing capacity. It is widely known that one of the main causes of fire-induced performance loss is concrete spalling, or the sudden ejection of surface material at high temperatures [23, 24]. The accumulation of pore pressure during rapid heating is often associated with spalling. High-strength concrete is more prone to explosive spalling and, consequently, less fire resistant than normal-strength concrete because of its inherent decreased permeability, which makes it more vulnerable to such pressure buildup [25-27].

Stiffness and boundary restraint circumstances also affected the slab fire performance. Because compressive constraint from adjacent structures reduces the effects of thermal expansion, one-way constrained slabs are frequently more fire resistant than unrestrained slabs [28-30]. While the lateral cover adds less to the overall performance, the bottom concrete cover has a significant impact on the fire resistance of externally exposed sections in terms of section configuration [31].

Current design codes provide simplified predictive methods for the fire resistance of slabs. Eurocode 2 [32] defines temperature distribution profiles through slab thickness (or beam/column cross-sections) for various fire resistance ratings, which typically last 30 or 60 minutes under standard fire exposure. The ACI Committee 216 [33] technique assesses the slab fire resistance based on the relative bending capacity, defined as the ratio of the moment from applied loads to the section's moment capacity. The cover thickness was determined by the aggregate type.

Despite the substantial body of research on the fire behaviour of reinforced concrete slabs, most existing studies

have examined geometric factors (e.g., slab thickness or reinforcement cover) or material properties (e.g., concrete strength) in isolation. Few studies have fully assessed the combined effect of these parameters on the time-dependent degradation of flexural ability during normal fire exposure. This restriction makes it more difficult to build optimal slab layouts for increased structural safety and efficiency, as well as to fully comprehend how design parameters interact to affect fire endurance.

To close this gap, this study examines the relationship between the bending strength degradation of reinforced concrete slabs exposed to the ISO 834 standard fire exposure and concrete thickness, concrete cover, and concrete compressive strength. It is anticipated that the results would enable improvements to the prescriptive code provisions for reinforced concrete slab systems and offer quantitative data for performance-based fire design.

2. Methodology

This study examined the fire performance of an 8-meter-effective-span, simply supported reinforced concrete slab. The reference slab was intended to have a concrete compressive strength of 30 MPa and be 200 mm thick. A 15 mm concrete cover, measured from the outside surface of the reinforcement, was installed over the tensile reinforcement, which was made up of high-strength deformed bars (BjTS 420A) with a yield stress of 420 MPa. 16 mm diameter bars spaced 125 mm centre-to-centre across the slab width made up the reinforcing plan. Parametric changes in the slab thickness, concrete cover, and compressive strength were tested against this slab configuration, which served as the control case.

The loading configuration followed the provisions of the ASCE 7-16 [34]. The dead load consisted of the self-weight of the slab plus a superimposed dead load of 1.0 kN/m². The live load was calculated as 2.4 kN/m², which corresponds to the office occupancy classification. For the fire design assessment, the load combination recommended for accidental fire situations was adopted as follows:

$$q_{fire} = D + 0.4L \quad (1)$$

Where D is the total dead load, including self-weight and additional dead load, and L is the live load. This combination shows the reduction in live load during a fire.

The concrete slab is exposed to fire with a temperature according to the ISO curve [35], as shown in Figure 1. The empirical method proposed by Wickström [36] was used to estimate the temperature distribution of the concrete. This approach was chosen for its ease of use, suitability for ISO 834 fire conditions, and track record of accuracy in forecasting concrete temperature profiles under typical fire exposure, as demonstrated by earlier experimental and numerical research.

The surface temperature (T_w) of the concrete exposed to a standard fire was calculated as

$$T_w = (1 - 0.0616t_h^{-0.88})T_f \quad (2)$$

Where T_f is the fire temperature ($^{\circ}\text{C}$), whereas t_h is the exposure period in hours.

The concrete temperature (T_c) at time t_h for any depth x (m) within the slab is determined by

$$T_c = (0.18 \ln(t_h/x^2) - 0.81)T_w \quad (3)$$

This approach makes the assumption that heat transfer is solely reliant on the thermal properties of the concrete. Additionally, it was assumed that the temperature of the steel reinforcement was the same as that of the neighbouring concrete at the same depth, which is often the case when assessing the fire performance of reinforced concrete parts.

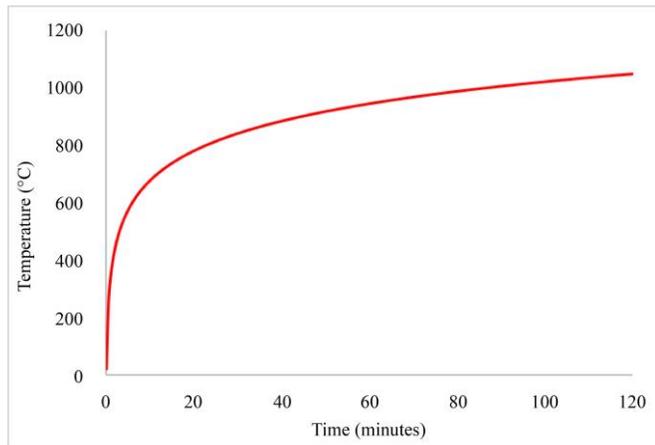


Fig. 1 ISO 834 standard fire curve

The analysis took into consideration temperature-dependent reduction factors for both reinforcing steel and concrete in order to account for the decrease in material strength at high temperatures. These variables are the proportions between the material's strength at temperature T and its strength at room temperature. The strength reduction factor ($k_{c,T}$) in concrete is described as follows.

$$k_{c,T} = 1 \quad \text{For } T < 350^{\circ}\text{C} \quad (4)$$

$$k_{c,T} = (910 - T)/560 \quad \text{For } T > 350^{\circ}\text{C} \quad (5)$$

For steel reinforcement, the yield strength reduction factor ($k_{y,T}$) is given by

$$k_{y,T} = (720 - T)/470 \quad (6)$$

Where T is the substance's temperature in degrees Celsius. These formulas are comparable to empirically

validated degradation models often used in structural fire engineering and ensure that the temperature-dependent loss of load-bearing capability is adequately reflected in the bending strength measurement.

Temperature-dependent material degradation variables were taken into account while calculating the slab's flexural capacity at elevated temperatures (M_f). The capacity was calculated using the traditional rectangular stress block method, which was adjusted to take into consideration the concrete's decreased compressive strength and the reinforcing steel's decreased yield strength in the event of a fire. The expression for the moment capacity is

$$M_f = A_s f_{y,T} (d - a_f/2) \quad (7)$$

Where A_s is the area of tensile reinforcement, $f_{y,T}$ is the yield strength of reinforcement reduced for temperature, d is the effective depth of the cross section, and a_f is the depth of the equivalent rectangular stress block under fire conditions, calculated as

$$a_f = A_s f_{y,T} / 0.85 f'_c b \quad (8)$$

Where f'_c is the characteristic compressive strength of concrete under fire conditions, and b is the width of the slab section.

3. Results and Discussion

3.1. Temperature Distribution and Bending Strength Degradation

Together with the reference standard fire curve, Figure 2 shows the temperature-time relationship for the slab surface and embedded steel reinforcement under the ISO 834 standard fire exposure. In the first heating phase, the surface temperature of the concrete rose rapidly and reached about 680°C in 20 minutes, and more than 900°C in 60 minutes. After 120 minutes of exposure, the surface temperature almost reached $1,000^{\circ}\text{C}$, which is in good agreement with the typical fire curve.

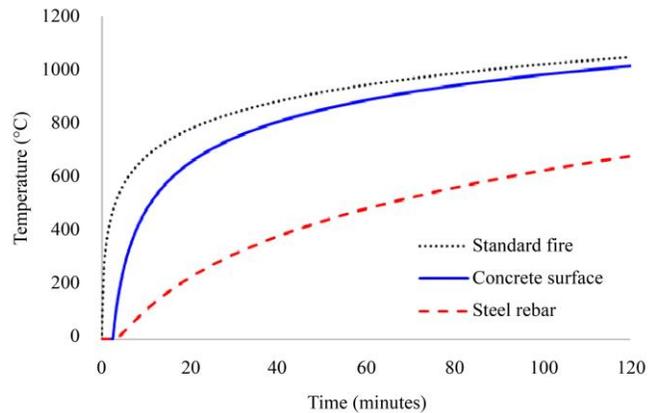


Fig. 2 Temperature distribution at the concrete surface and steel reinforcement under ISO 834 standard fire exposure

High heat insulation properties of the surrounding concrete cover cause steep increases in temperature of steel reinforcements. Reinforcement temperature increases below 250 °C for 20 minutes and rises to almost 500 °C after 60 minutes. Reinforcement temperatures after 120 minutes of exposure were at 670 °C, which is significantly lower than the temperature of the surface.

Significantly, the substantial difference between the surface and the steel reinforcements' inner temperature is key to sustaining the structural integrity of the slab. The major contributor to this temperature differential is the concrete's poor thermal conductivity, which results in slower heat transmission and prolongs the degradation of the steel's mechanical properties. The longer the reinforcement is exposed, the lower the thermal gradient across the cross-section and the bending strength.

Figure 3 shows the benchmark slab configurations, bending strength reduction over time, and the corresponding design moment from the fire load combination capacities limits as per the ISO 834 standard fire exposure. The initial flexural capacity at room temperature was around 140 kNm. There was a significant strength reduction of almost 20 kNm to about 115 kNm in the first 20 minutes. This initial reduction occurs because of the quick rise of surface temperatures in Figure 2, and while the reinforcement temperature is still below the critical levels, it is beginning to have a significant effect on the yield strength of the steel.

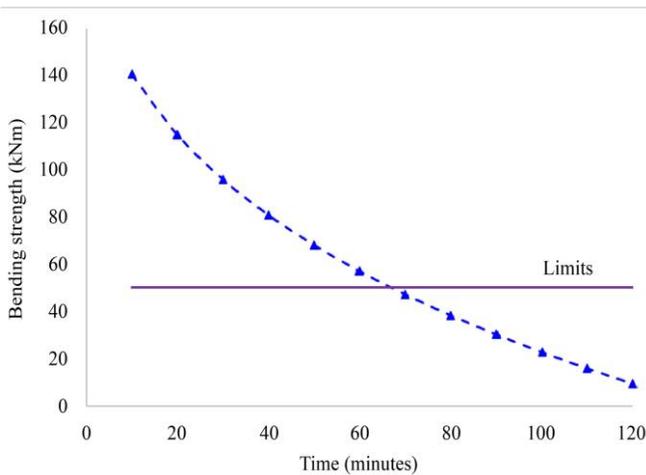


Fig. 3 Time-dependent bending strength degradation of the concrete slab under ISO 834 standard fire exposure

As the temperature of the reinforcement continued to rise, the decline remained ongoing, hitting nearly 56 kNm at 60 min, nearing the capacity threshold of 50 kNm. The intersection of the bending strength curve and the limit line occurred at around 65 minutes of fire exposure. Since it marks the start of structural inadequacy under the imposed service loads during a fire, this point chooses the slab's fire resistance rating for a defined loading condition.

The residual capacity dropped below the design limit after 65 minutes, suggesting that prolonged exposure to the fire resulted in considerable deflection and possible failure. The capacity decreased by more than 90% from its starting value to about 10 kNm after 120 minutes.

3.2. Effect of Concrete Slab Thickness

Figure 4 illustrates the bending strength degradation of reinforced concrete slabs with thicknesses of 180, 200, and 220 mm under the ISO 834 standard fire exposure, along with the design capacity limit. The impact of slab thickness on residual bending strength was noticeable during the first heating cycle.

The maximum starting capacity (~158 kNm) was shown by the 220 mm slab, which was followed by the 200 mm (~142 kNm) and 180 mm (~124 kNm) slabs. The thicker slabs' increased effective depth and reinforced lever arm, which improve the flexural resistance in ambient conditions, are the reason for the discrepancy in the initial capacity.

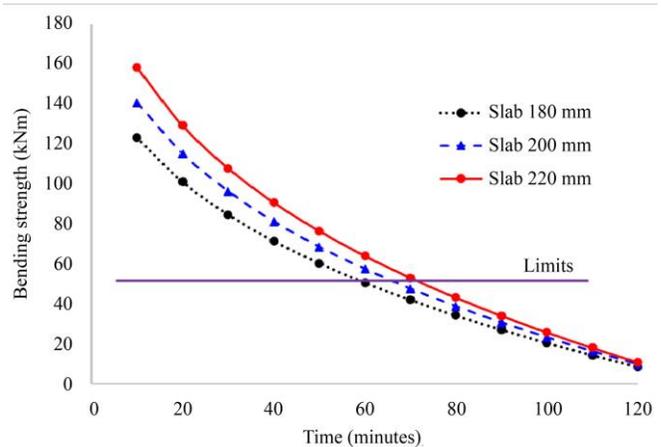


Fig. 4 Effect of slab thickness on bending strength degradation under ISO 834 standard fire exposure

Since every slab has the same cover, this is not because of increased cover protection; rather, it is because of a bigger cross-sectional mass, which serves to prolong stiffness by delaying the heating of the tension zone.

The slab variances become less noticeable when heat spreads uniformly throughout the section with extended exposure, and the temperatures of the reinforcement consistently reach critical values. Within 100 minutes, the residual strengths for all thicknesses converged to less than 20 kNm.

Regarding fire resistance rating and the time the residual bending capacity fell below the design limit, the 180 mm slab failed at about 60 minutes, the 200 mm slab at 65 minutes, and the 220 mm slab at 70 minutes. Thickening the plate from 180 to 220 mm results in an increase in fire resistance of 10 minutes.

3.3. Effect of Concrete Cover

Figure 5 presents the degradation of bending strength for reinforced concrete slabs with concrete covers of 10 mm, 15 mm, and 20 mm under ISO 834 standard fire exposure. Increasing the cover thickness slightly reduces the effective depth of reinforcement, since the overall slab thickness remains constant. Consequently, under ambient conditions, the slab with a 20 mm cover exhibits a marginally lower initial flexural capacity compared to the 10 mm and 15 mm cover cases.

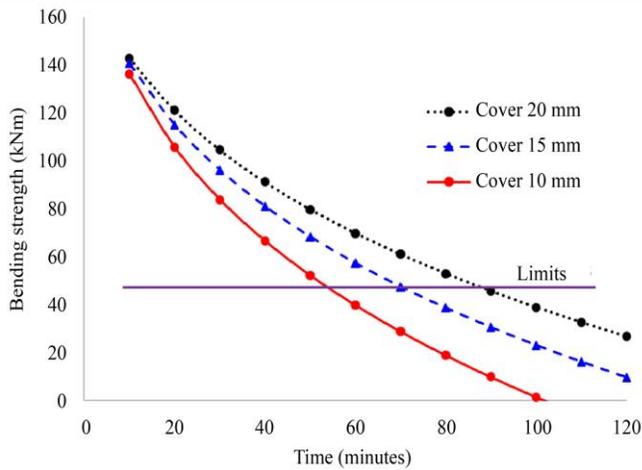


Fig. 5 Effect of concrete cover on bending strength degradation under ISO 834 standard fire exposure

During the early stages of fire exposure, the reinforcement temperature remains relatively low, and the reduction in steel yield strength is minimal. As a result, the residual bending capacities of the three configurations are initially similar. However, as heating progresses, the influence of concrete cover becomes increasingly significant.

A thicker cover provides improved thermal insulation, delaying the temperature rise in the reinforcement and reducing the rate of steel strength degradation. Consequently, slabs with greater cover thickness retain a higher proportion of their initial bending capacity over time.

The difference becomes evident when evaluating fire resistance. The slab with a 10 mm cover reaches the limiting bending capacity at approximately 50 minutes, whereas the 15 mm cover extends the fire endurance to about 75 minutes, and the 20 mm cover further delays failure to approximately 90 minutes. Increasing the cover from 10 mm to 15 mm results in an improvement of roughly 25 minutes, while a further 5 mm increase from 15 mm to 20 mm provides an additional 15 minutes of fire resistance. These findings highlight the dual role of concrete cover: while slightly reducing ambient flexural capacity due to reduced effective depth, it significantly enhances fire performance by improving thermal protection of the reinforcement.

3.4. Effect of Concrete Compressive Strength

Figure 6 shows the flexural strength of concrete slabs with compressive strengths of 25, 30, and 35 MPa under temperature exposure conditions according to ISO 834 standards. The results indicate a decrease in compressive strength during exposure. At the initial heating conditions, higher compressive strengths have slightly better flexural resistance. However, as the temperature increases, this difference disappears, where all high-strength concrete compressive strengths have a similar performance.

This strength convergence occurs due to a drastic decrease in the compressive strength of concrete after temperatures exceed 300–400 °C, regardless of its initial strength. Above this threshold, the mechanical behaviour of concrete is completely controlled by heat-induced physicochemical transformations, such as cement paste dehydration, aggregate decomposition, and microcracking. These degradation processes rapidly and uniformly remove stiffness and cohesion, so that concrete with different initial strengths exhibits similar thermal damage patterns.

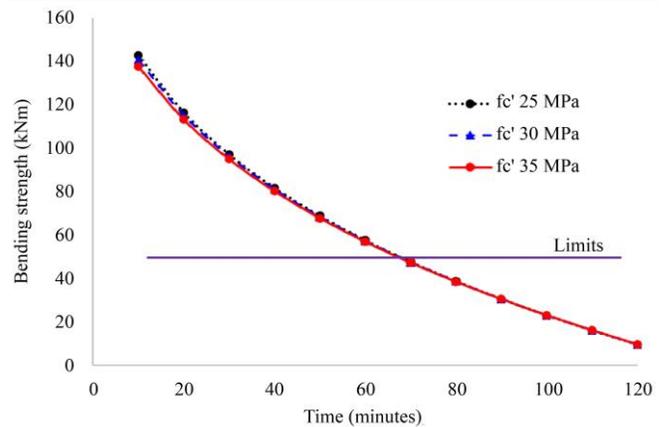


Fig. 6 Effect of concrete compressive strength on bending strength degradation under ISO 834 standard fire exposure

In the final stage of a fire, when the reinforcement temperature exceeds 500–600°C, the structural capacity of the slab is determined by the reduction in the yield strength of the steel, rather than by the residual strength of the concrete. Consequently, the influence of the concrete compressive strength on the flexural performance becomes negligible. This is evident from all specimens reaching the design bending moment limit at approximately the same time, approximately 65 minutes, regardless of the variation in compressive strength. This finding confirms that the fire resistance of reinforced concrete slabs is primarily controlled by the thermal insulation of the reinforcement and the degradation of the steel due to high temperatures, rather than by the initial compressive strength of the concrete. Therefore, improving the concrete quality alone will not significantly improve the structure's fire performance.

3.5. Design Implications

This study identified three key parameters affecting the fire resistance of reinforced concrete slabs: slab thickness, concrete cover, and concrete compressive strength. Among these, concrete cover proved to be the most dominant factor. While increasing cover thickness slightly reduces the initial flexural capacity due to the reduction in moment lever arms, its thermal insulation benefits are far more significant because it delays the thermal degradation of reinforcement. Increasing cover thickness from 15 mm to 20 mm, for example, extended the fire resistance by up to 25 minutes. Conversely, reducing it to 10 mm reduced it by 10 minutes. Therefore, to improve fire resistance performance without changing the slab geometry, optimizing concrete cover thickness should be a top priority.

Slab thickness also contributes to increased fire resistance, although the effect is not as significant as concrete cover. Increasing slab thickness from 180 mm to 220 mm, for example, increased fire resistance by up to 10 minutes. This benefit stems from greater thermal mass, which slows the heating rate in the tension zone, allowing for longer structural stiffness. However, this positive effect only applies if the concrete cover is not compromised. Since all specimens in this study maintained the same cover thickness, increasing slab thickness proved effective in preventing failure without compromising the protection of the reinforcement.

In contrast, concrete compressive strength was shown to have a negligible effect on fire resistance. Although high-strength concrete had a superior flexural capacity at room temperature, this advantage rapidly disappeared when temperatures exceeded 300–400°C. This convergence in thermal behaviour was demonstrated by all specimens, regardless of initial strength, which reached their design capacity at the same time, 65 minutes. These results reinforce previous findings that fire resistance is more determined by the effectiveness of the thermal insulation of the reinforcement than by the initial strength of the concrete itself.

From a design perspective, these results suggest that the fire resistance of reinforced concrete slabs is best improved by optimising the reinforcement cover rather than relying solely on increasing the slab thickness or concrete strength. However, the choice of cover must also consider serviceability, durability, and construction constraints of the cover. For cases where an increased fire rating is required without significantly increasing the self-weight or cost, targeted enhancement of the cover depth, combined with performance-based verification, may offer the most efficient solution.

4. Conclusion

This paper presents an evaluation of the fire performance of reinforced concrete slabs exposed to the ISO 834 standard

fire for different levels of slab thickness, concrete cover, and concrete compressive strength. The benchmark slab configuration was an 8 m span, simply supported slab, 200 mm thick, $f_c' = 30$ MPa, with a cover of 15 mm. The temperature distribution was calculated using Wickström's empirical method, and the temperature-dependent strength reductions for concrete and reinforcement were included to evaluate the reduction of bending capacity.

The main conclusions are as follows:

1. Thermal behaviour: While the surface temperature of the concrete followed the standard fire curve quite closely, the concrete cover's insulating effect caused a significant delay in the temperature of the reinforcing. This delay extended the time for the reduction of steel strength to occur, but as the heat progressively advanced deeper within the slab, the strength of the steel deteriorated.
2. Bending strength degradation: The benchmark slab's capacity gradually decreased, and at around 65 minutes, its residual strength dropped below the design limit, defining its fire-resistance rating. Degradation happened most quickly when the reinforcement temperature was beyond 500–600 °C.
3. Effect of slab thickness: The fire resistance increased by about 10 minutes when the slab thickness was increased from 180 to 220 mm. Although both slabs had the same cover depth, this benefit is due to the larger cross-sectional mass delaying heat penetration, which results in diminishing differences with time.
4. Effect of concrete cover: Cover depth had the most pronounced effect on fire resistance. Increasing the cover from 15 mm to 20 mm extended fire endurance by approximately 25 minutes, while reducing it to 10 mm shortened it by about 10 minutes. Although thicker covers reduce the lever arm slightly, they significantly enhance insulation to reinforcement.
5. Effect of concrete compressive strength: Fire endurance was barely affected by changes in the ambient compressive strength (25, 30, and 35 MPa). At around 65 minutes, all slabs hit the design limit, demonstrating that the reinforcement's thermal insulation had a greater influence on fire performance than the ambient concrete strength.

According to the analytical findings, the reinforcing cover has the biggest impact on the slab fire performance, followed by the slab thickness, while the concrete's compressive strength has the least impact. Since even modest increases can greatly increase the fire resistance duration, increasing the cover depth is the most effective and cost-effective way to improve fire endurance.

While they also boost performance, moderate slab thickness increases have diminishing returns. On the other hand, once high temperatures are achieved, a stronger concrete

does not improve fire resistance. Optimizing the reinforcing cover within code bounds offers a workable way to get the required fire ratings for design applications without significantly increasing weight or cost.

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Ethical Approval

All analyses were performed in accordance with academic integrity. The authors attest that the information provided is authentic and has not been altered or fabricated.

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Author Contribution

Riza Suwondo: Conceptualization, Methodology, Data curation, Writing – original draft. Made Suangga: Writing – review and editing, Supervision. Irpan Hidayat: Writing – review and editing.

Data Availability

Data analysis <https://zenodo.org/records/16789361>

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