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Investigating the Impact of Temperature Variations on the Load-Carrying Capacity of Plain Concrete Beams

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Abstract

Fires are among the most common and devastating accidents that unexpectedly impact service structures, often starting with little effort but requiring substantial time, resources, and expense to control. In Ethiopia, fire accidents have frequently caused severe damage to buildings, emphasizing a critical issue. While concrete behavior under normal conditions is well understood and applied in design, its performance under extreme heat remains less explored, posing challenges in creating structures with sufficient fire resistance. The repeated occurrence of destructive fires, resulting in both loss of life and structural failures, highlights the urgency of designing buildings that can withstand high temperatures. This paper examines how elevated temperatures affect the load-carrying capacity of plain concrete beams, focusing on their performance after exposure to intense heat. Factors such as compressive strength, vertical displacement, and load-carrying capacity were analyzed using load-displacement curves under varying temperature levels and exposure durations. Key variables, including concrete grade, temperature, and exposure time, were considered to assess concrete strength in extreme conditions. An experimental study on plain concrete beams with grades C-15, C-25, C-30, and C-40 was conducted under temperatures of 100°C, 200°C, and 300°C for four and eight hours. The results revealed that as temperature and exposure time increased, load-carrying capacity significantly declined, with lower-grade concrete suffering more strength loss while higher-grade concrete exhibited better fire resistance. This study underscores the importance of incorporating fire performance into building codes to enhance structural adaptability in fire-prone regions.

Keywords: Concrete Grade, Load Carrying Capacity, Plain Concrete, Temperature.

Introduction

Engineers have increasingly recognized the importance of fire-resistant design for structures following numerous fire incidents that resulted in loss of life and severe damage to buildings (1, 2). Concrete structures generally perform well during fires due to concrete's non-combustible nature and low thermal conductivity, which slows heat transfer to internal steel reinforcements if the concrete cover remains intact (3, 4). However, despite concrete's inherent fire resistance, structural components must still be designed to withstand fire-induced stresses, temperature-related strength reductions, and unexpected deformations (5, 6). Fire protection strategies often involve prescriptive measures, such as specifying non-combustible materials, adding insulation, and installing fire suppression systems (7). The variability of fire conditions makes designing for fire particularly challenging, necessitating considerations beyond typical service loads. For optimal safety, fire resistance should be integrated into the initial design phase, with attention given to the fire performance of both reinforced concrete and its components under high temperatures (8).

Concrete is a widely used material in high-rise and special-purpose structures due to its strength and durability under normal conditions (9, 10). However, building codes addressing fire resistance are sometimes overlooked, leading to errors (11). For example, a concrete slab may meet strength requirements but fail to satisfy the fire resistance thickness required by building codes (12). Under high temperatures, concrete properties can signif-

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icantly change, affecting its strength, elasticity, and structural integrity (13). Prolonged or extreme heat can lead to cracking, loss of bearing capacity, and structural failure, especially in critical applications like nuclear reactors, petrochemical vessels, and tunnels where temperatures are greater than 1000°C (14, 15). The fire response of concrete depends on the temperature increase rate, fire duration, and its insulating properties (16). Although concrete's low thermal conductivity provides some protection for internal steel reinforcement, understanding the changes in its properties under high temperatures is essential for designing fire-resistant structures and predicting post-fire behavior (17, 18).

Concrete is one of the most widely used construction materials due to its strength, durability, and cost-effectiveness. However, plain (unreinforced) concrete is inherently brittle and particularly sensitive to environmental factors such as temperature fluctuations. With the increasing impact of global climate change, the structural performance of concrete under varying thermal conditions has become a growing area of concern. Recent advancements have contributed significantly to this field—studies utilizing scanning electron microscopy (SEM) and X-ray computed tomography have revealed how high temperatures lead to microcracking and weaken the bond between cement paste and aggregates (19, 20). Thermo-mechanical modeling has furthered understanding of crack initiation and propagation under thermal stress. High-temperature exposure has been shown to degrade mechanical properties such as compressive strength and modulus of elasticity due to the breakdown of hydration products. On the other end of the spectrum, research into freezing and thawing cycles has demonstrated that cold environments can cause surface scaling and internal cracking. Non-destructive testing methods, including ultrasonic pulse velocity and infrared thermography, have also enhanced real-time monitoring of thermal damage in concrete structures (21). Despite these breakthroughs, several critical knowledge gaps remain. While many studies have explored the effects of extreme temperatures, there is limited understanding of how moderate and cyclic thermal conditions—common in real-world environments—affect the structural behavior of plain concrete. Most existing research focuses on reinforced or fiber-reinforced concrete, whereas the behavior of plain concrete beams under flexural loads and varying temperatures is underexplored (22). Additionally, the combined effects of thermal and mechanical loading, as well as the role of non-uniform thermal gradients in stress distribution and crack formation, are not yet fully understood. These gaps highlight the need for focused investigation. This study aims to address these deficiencies by experimentally evaluating the load-carrying capacity of plain concrete beams subjected to elevated, reduced, and cyclic temperature variations. The results are expected to provide insights that will contribute to more resilient and thermally-informed structural design practices.

The current study focuses on the immediate effects of temperature exposure on the load-carrying capacity of plain concrete beams, such as strength degradation and cracking behavior following short-term thermal events. However, to enhance the scope and applicability of the research, future studies should consider the long-term impacts of repeated or prolonged temperature fluctuations, including gradual deterioration due to thermal cycling, cumulative microstructural damage, and changes in durability properties over time. Incorporating this into the limitations or future work section would provide a more comprehensive understanding of how concrete beams perform not just under isolated temperature events, but also in real-world conditions where long-term thermal exposure is common (23). This study aims to help structural engineers understand the impact of factors such as concrete grade, extreme temperatures, and duration on the load-carrying capacity of plain concrete beams subjected to variable temperatures. By shedding light on how fire affects concrete beams and identifying critical parameters for fire-resistant design, the findings could encourage engineers to consider concrete grades and material properties in their designs. The research outcomes are valuable for designing fire-resistant reinforced concrete beams, assessing structural integrity after fire incidents, guiding fire safety institutions, and serving as a reference for future studies in the field.

Methodology

Ordinary Portland Cement (OPC) with a strength grade of 42.5MPa was used as the binding material. It possesses cohesive and adhesive properties, enabling it to bind aggregates into a solid mass. Aggregate grading was determined through sieve analysis, which classifies particles based on size. The fineness modulus, obtained by summing retained material on all sieves and dividing by 100, indicates aggregate fineness, coarseness, and uniformity. Aggregates serve as inert filler that enhances concrete strength, minimizes volume changes due to moisture variations, and improves durability. Crushed basaltic stone was used as coarse aggregate, classified as siliceous. For different concrete grades, specific aggregate sizes were selected: C-15 (≤38.5mm), C-25 (≤25mm), C-30 (≤19.5mm), and C-40 (≤12.5mm). River sand was used as fine aggregate, and in some cases, it was washed to remove silt that could weaken the concrete. Concrete specimens were prepared in cylindrical and rectangular beam forms (4). Cylindrical specimens had diameters of 100mm and 200mm with heights of 200mm and 300mm, respectively. Rectangular beam specimens measured 100mm in thickness, 100mm in depth, and 500mm in length. Three trial specimens were tested to obtain representative values. In total, 21 plain concrete beams were produced for each grade, resulting in 84 specimens across all four grades (C-15, C-25, C-30, and C-40).

For thermal testing, specimens were exposed to 100°C, 200°C, and 300°C in an oven-dry machine due to furnace size limitations. Two exposure durations—four hours and eight hours—were selected based on previous Ethiopian research, which indicated that medium fire accidents typically last three to four hours. The extended duration provided a broader understanding of temperature effects. Flexural strength tests were conducted to determine the maximum load-carrying capacity and load-displacement response of the plain concrete beam specimens. Concrete mix design involved selecting appropriate proportions of cement, water, aggregates, and potential admixtures to achieve the desired properties (7). During mixing, sand, cement, and aggregates were first dry-mixed for three minutes before adding water to form a homogeneous mixture. A slump test was conducted to ensure the desired consistency before casting. Fresh concrete was then poured into standard cylindrical and beam molds. The cylindrical molds, measuring 150mm × 300mm and 100mm × 200mm, were filled in three layers, each compacted with 25 blows using a shaker. Similarly, rectangular beam molds (100mm × 100mm × 500mm) were filled and compacted. To facilitate easy de-molding, the molds were coated with boiled oil before pouring. The specimens remained in the molds for 24 hours at room temperature before being de-molded for further testing as shown in Figure 1.

Figure 1: Cylindrical Concrete and Plain Concrete Beam Specimens

Curing is crucial for concrete strength development, as it facilitates hydration. A longer curing period results in higher strength, with concrete achieving about 90%-95% of its full strength after 28 days. To ensure proper hydration, all concrete samples were submerged in a water-filled curing tank for 28 days. Fire performance testing of construction materials is typically conducted using burning furnaces with temperature sensors and thermocouple (20). In this experiment, an oven-dry machine capable of reaching 300°C was used to expose plain concrete beam specimens to controlled temperatures (9). The specimens were subjected to three temperature levels 100°C, 200°C, and 300°C with 2 exposure durations: four hours and eight hours as shown in Figure 2.

Figure 2: Oven Dry Machine Used for Temperature Exposure for a Plain Concrete Beam Specimens

The testing procedure for plain concrete beam specimens exposed to specific temperatures and durations followed these steps:

- **Mix Design:** The appropriate mix was prepared for each concrete grade.
- **Mixing and Casting:** Concrete ingredients were mixed as per the design specifications, and beam specimens (100mm × 100mm × 500mm) were cast into molds.
- **Curing:** Samples were submerged in a water tank for 28 days to ensure proper hydration and strength development.
- **Pre-Testing Preparation:** After curing, samples were air-dried for one day to eliminate surface moisture and prevent interference during testing.
- **Temperature Exposure:** Specimens were placed in an oven-dry machine (up to 300°C) and heated for four or eight hours.
- **Cooling:** After exposure, samples were cooled in open air to reach a suitable testing temperature.
- **Weight Measurement:** Each sample was weighed to assess weight loss due to heat exposure.
- **Flexural Strength Testing:** Cooled specimens were tested in a flexural strength testing machine to determine load-carrying capacity.

This procedure enabled the study to evaluate the impact of temperature and duration on the flexural strength of plain concrete beams with different compressive strengths (C-15, C-25, C-30, and C-40) as shown in Figure 3.

Figure 3: Plain Concrete Specimens Ready for Testing and on Testing Machines

Various equipment was used throughout this study to support different stages, including mixing, casting, heating, measuring, handling, and testing.

- **Concrete Mixer:** A $0.5m^3$capacity mixer was used to prepare the concrete mixture.
- **Molds:** Steel and plastic molds were utilized, including:
  Cylindrical molds (100mm diameter × 200mm height).
  - Rectangular beam molds (100mm depth × 100mm thickness × 500mm length).
- **Temperature Exposure Equipment:** An oven-drying machine capable of reaching 300°C was used for heating the concrete specimens.
- **Universal Testing Machine:** This machine measured load-carrying capacity, stress-strain response, load-displacement, and load-time characteristics. For accuracy, specimens were centrally positioned to ensure uniform load application as in Figure 4.

Figure 4: Test Setup for Plain Concrete Beam

Results and Discussion

This section presents the experimental findings, organized into tables and graphs for clarity. It focuses on the performance of plain concrete beam specimens and examines factors affecting their load-carrying capacity under different temperature exposures and durations (21). Additionally, it discusses changes in the physical and chemical properties of the specimens, including weight loss and reductions in load capacity.

All temperature data are directly derived from the conducted experiments. The tested specimens were plain concrete beams measuring 100mm in depth, 100mm in thickness, and 500mm in length. To evaluate flexural strength under fire conditions, four sets of concrete cylinder samples with different compressive strengths were prepared. Three plain concrete beam samples were tested at each temperature and duration to determine representative flexural strengths. Due to potential variations in mix design and environmental conditions, the target compressive strengths were not fully achieved. Table 1 below compares the planned and actual compressive strength values of the specimens (22).

Table 1: Compressive Strength and Maximum Load Carrying Capacity of Plain Concrete Beam

Sample Group	Targeted Compressive strength (MPa)	Actual Compressive strength (MPa)	Max load carrying capacity (KN)
Group one	15	12.6	5.03
Group two	25	24.15	6.27
Group three	30	29	7.733
Group four	40	38.9	9.747

The table above demonstrates a direct correlation between actual compressive strength and the maximum load-carrying capacity of the beams. The results indicate that as compressive strength increases, the load-carrying capacity of the plain concrete beam samples also improves.

The data shows:

- A 47.82% increase in compressive strength for the first group results in a 19.7% increase in load-carrying capacity.
- A 16.72% increase in compressive strength for the second group leads to an 18.9% rise in load-carrying capacity.
- A 25.45% increase in compressive strength for the third group results in a 20.6% improvement in load-carrying capacity.

The load-displacement graph for the plain concrete beam at room temperature is presented in Figure 5.

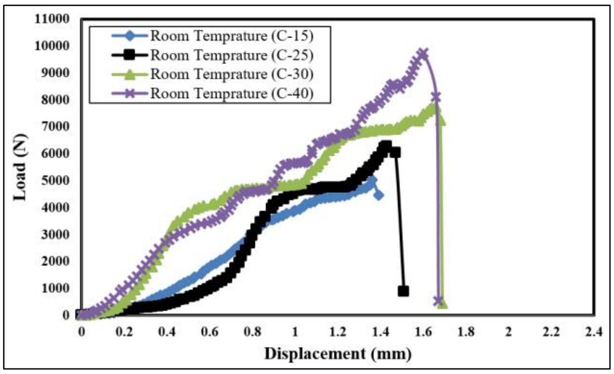

Figure 5: Load-Displacement Graph of Plain Concrete Beam under Room Temperature

This study examines the effect of temperature on the performance of plain concrete beams. The fire exposure duration and concrete grade remain constant, while the exposure temperature varies. Four concrete grades were tested at three temperature levels 100°C, 200°C, and 300°C each for two durations: four hours and eight hours (23).

The following graphs illustrate the load-displacement behavior of C-15 concrete beams (15MPa compressive strength) exposed to these temperatures. For comparison, the graphs also include the load-displacement behavior of beams at room temperature to highlight the impact of heat on load-carrying capacity.

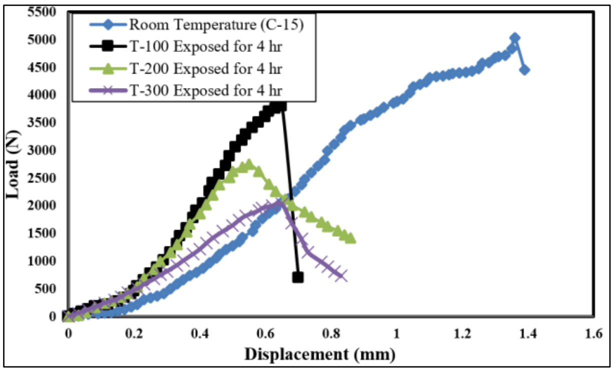

Figure 6: Load-Displacement Graph of C-15 Plain Concrete Beam Subjected to Different Temperature for Four-Hour Duration

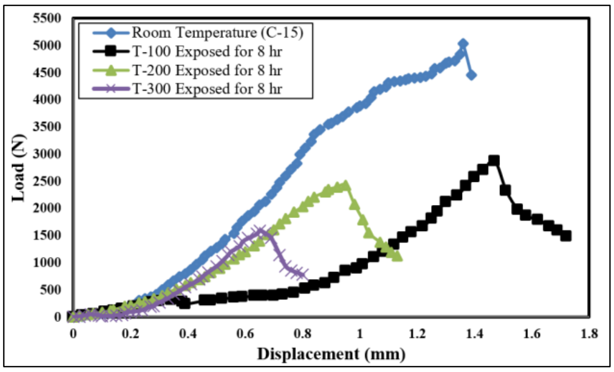

Figure 7: Load-Displacement Graph of C-15 Plain Concrete Beam Subjected to Different Temperature for Eight Hour Duration

The graphs Figure 6 and Figure 7 above highlight the effect of temperature and fire exposure duration on the performance of plain concrete beams under extreme conditions. The data indicates that both factors significantly influence the beams' maximum load-carrying capacity (24).

As temperature and exposure time increase, the load-carrying capacity decreases, and the load-displacement curve becomes more compact. The Table 2 below summarizes the load-carrying capacity values at different temperatures and exposure durations.

Table 2: Percentage Reduction of C-15 Plain Concrete Beam Subjected to Different Temperature and Duration

Target Group	Exposed Temperature (^{0}C)	Load carrying capacity (KN)		% Reduction of load carrying capacity	
		For 4Hr.	**For 8Hr.**	For 4Hr.	For 8Hr.
C-15	Room	5.03	5.03	0	0
C-15	100	3.803	2.876	24.39	42.82
C-15	200	2.747	2.423	45.38	51.82
C-15	300	2.036	1.594	59.52	68.31

The Table 2 clearly shows that as temperature increases, the load-carrying capacity of the plain concrete beam decreases correspondingly. However, a plain concrete beam exposed to 200°C for eight hours shows a slight increase in load-carrying capacity. The following two graphs illustrate the load-displacement behavior of C-25 concrete beams (25MPa compressive strength) exposed to 100°C, 200°C, and 300°C for both four-hour and eight-hour durations (24). To highlight the reduction in residual compressive strength and changes in the load-displacement pattern, the graphs as in Figure 8 also include data for a plain concrete beam at room temperature.

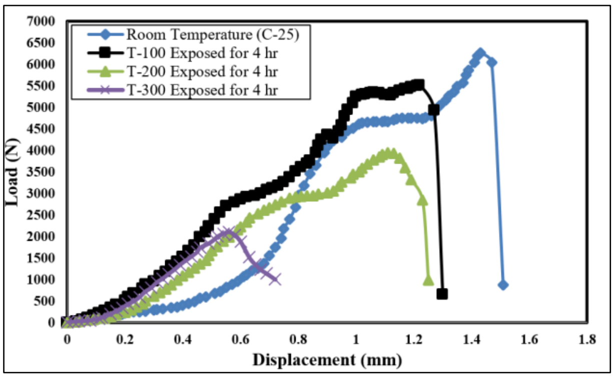

Figure 8: Load-Displacement Graph of C-25 Plain Concrete Beam with Different Temperature for Four Hour Duration

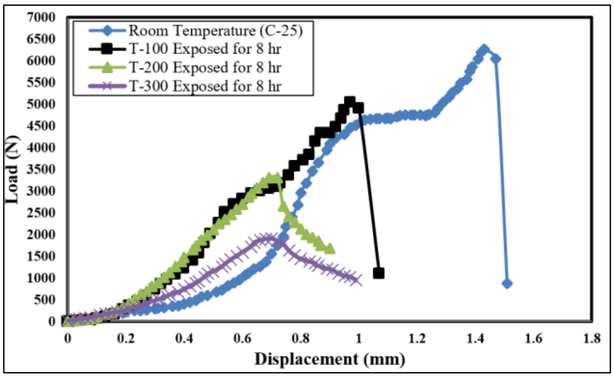

Figure 9: Load-Displacement Graph of C-25 Plain Concrete Beam with Different Temperature for Eight Hour Duration

Figure 9 and Figure 10 clearly show the effect of temperature and fire exposure duration on the performance of plain concrete beams under elevated conditions. The graphs indicate that as exposure temperature and duration increase, the maximum load-carrying capacity of the beams decreases, and the load-displacement curve becomes more compact (24). The Table 3 below summarizes the load-carrying capacity values for different temperatures and exposure durations.

Table 3: Percentage Reduction of C-25 Plain Concrete Beam with Different Temperature and Duration

Target Group	Exposed Temperature (⁰C)	Load carrying capacity (KN)		% Reduction of load carrying capacity	
		For 4Hr.	For 8Hr.	For 4Hr.	For 8Hr.
C-25	Room	6.27	6.27	0	0
C-25	100	5.515	5.041	12.04	19.6
C-25	200	3.942	3.307	37.13	47.25
C-25	300	2.111	1.907	66.33	69.5

The Table 3 shows that higher temperatures cause a more significant reduction in the load-carrying capacity of plain concrete beams. Similarly, prolonged exposure to elevated temperatures results in an even greater decrease in this capacity. A beam with a compressive strength of 25MPa exhibits better residual load-carrying performance after exposure than a beam with a compressive strength of 15MPa. The 25MPa beam retains approximately 2kN of compressive strength, allowing it to support loads up to this value even after fire exposure. The following two graphs illustrate the load-displacement behavior of C-30 concrete (30MPa compressive strength) under temperatures of 100°C, 200°C, and 300°C, with exposure times of four and eight hours. For comparison, the graphs also show the load-displacement behavior of plain concrete beams at room temperature, highlighting how residual compressive strength and load-displacement patterns are affected by heat exposure (24).

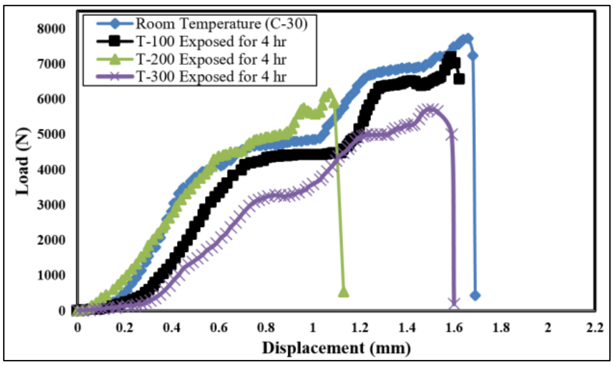

Figure 10: Load-Displacement Graph of C-30 Plain Concrete Beam Subjected to Different Temperature for Four Hour Duration

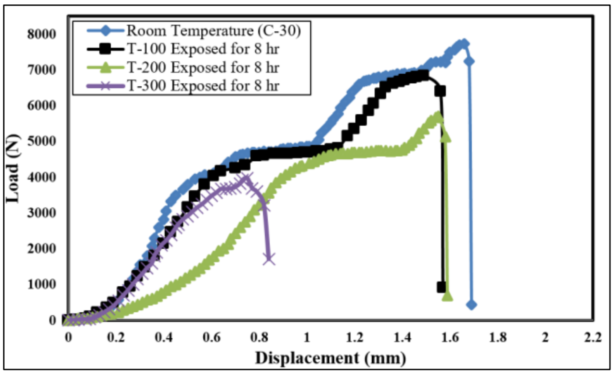

Figure 11: Load-Displacement Graph of C-30 Plain Concrete Beam Subjected to Different Temperature for Eight Hour Duration

The graphs Figure 10 and Figure 11 clearly demonstrate the impact of temperature and fire exposure duration on the performance of concrete under fire conditions. Higher exposure temperatures and longer durations lead to a greater reduction in the residual load-carrying capacity of plain concrete beams, with the load-displacement curve becoming more compact. Notably, in the load-displacement graph, the performance of C-30 concrete exposed to 100°C for four hours closely matches that of concrete at room temperature. This suggests that, at this temperature and duration, the beam's load carrying capacity remains largely unaffected as in Table 4.

Table 4: Percentage Reduction of C-30 Plain Concrete Beam with Different Temperature and Duration

Target Group	Exposed Temperature (^{0}C)	Load carrying capacity (KN)		% Reduction of load carrying capacity	
		For 4Hr.	For 8Hr.	For 4Hr.	For 8Hr.
C-30	Room	7.733	7.733	0	0
C-30	100	7.192	6.829	6.99	11.7
C-30	200	6.182	5.697	2	26.32
C-30	300	5.719	3.974	26.04	48.61

The Table 4 illustrates that higher temperatures result in a greater reduction in compressive strength. C-30 concrete exposed to 100°C for four hours experiences the smallest loss in load-carrying capacity, retaining about 93% of its full strength. In contrast, concrete exposed to 300°C for eight hours suffers the most significant reduction, losing nearly half of its strength. Compared to medium-strength concrete (C-25), C-30 concrete maintains better residual load-carrying capacity after exposure, supporting loads up to 3.9kN, demonstrating its durability under high temperatures (22). The final two graphs depict the load-displacement behavior of C-40 concrete exposed to temperatures of 100°C, 200°C, and 300°C for four and eight hours. For comparison, the graphs also include data for plain concrete beams at room temperature, highlighting the reduction in residual compressive strength with increasing temperature exposure.

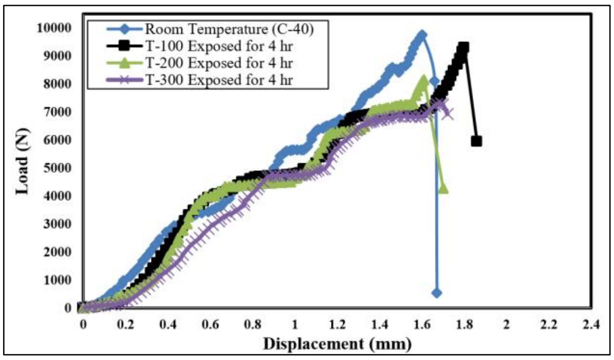

Figure 12: Load-Displacement Graph of C-40 Plain Concrete Beam with Different Temperature for Four Hour Duration

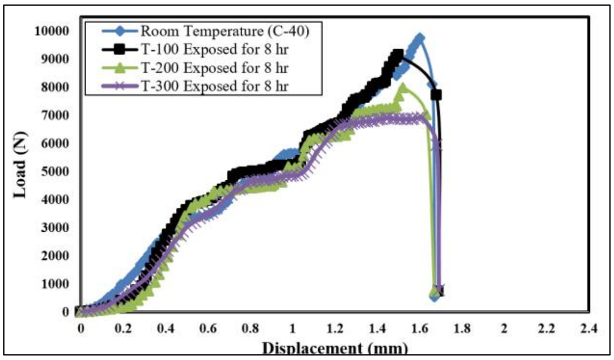

Figure 13: Load-Displacement Graph of C-40 Plain Concrete Beam Subjected to Different Temperature for Eight Hour Duration

The graphs in Figure 12 and Figure 13 above demonstrates the impact of temperature and fire exposure duration on the performance of concrete under elevated conditions. While higher temperatures and longer exposure times generally lead to a reduction in load-carrying capacity, the observed decrease in this case is minimal. The load-displacement graph does not indicate a significant drop in the beam's capacity. Notably, in the first graph of C-40 concrete exposed to 100°C for four hours, the results closely resemble those of concrete at room temperature. This suggests that, under these conditions, the beam's load-carrying capacity remains largely unaffected (24).

Table 5: Percentage Reduction of C-40 Plain Concrete Beam Subjected to Different Temperature and Duration

Target Group	Exposed Temperature (^0C)	Load carrying capacity (KN)		% Reduction of load carrying capacity	
		For 4Hr.	For 8Hr.	For 4Hr.	For 8Hr.
C-40	Room	9.747	9.747	0	0
C-40	100	9.155	9.145	6.07	6.17
C-40	200	8.143	7.992	16.45	18
C-40	300	7.314	6.925	24.93	28.95

The Table 5 demonstrates that higher temperatures result in a greater percentage reduction in load-carrying capacity. A plain concrete beam exposed to 100°C for four hours experiences the smallest reduction, retaining most of its strength. In contrast, a beam subjected to 300°C for eight hours suffers the most significant loss, with approximately 29% of its full load-carrying capacity diminished. However, this reduction is still lower than that observed in C-30 concrete, which loses nearly half of its capacity under the same conditions. Concrete with a compressive strength of 40MPa exhibits superior residual load-carrying capacity after exposure to elevated temperatures compared to lower-strength concretes (15MPa, 25MPa, and 30MPa). It can sustain loads up to 7kN, demonstrating strong performance under high-temperature conditions.

Physical and Chemical Changes of Plain Concrete Beam after Exposed to Temperature

Concrete's properties can change significantly when exposed to high temperatures, making it essential to understand how plain concrete beams respond to such conditions. This study investigated the impact of a maximum exposure temperature of 300°C. Up to this temperature, the concrete did not exhibit noticeable color changes, surface cracks, or spalling. However, the main effects observed included a reduction in the beam's load-carrying capacity and a decrease in its weight, which are discussed in more detail below.

Weight Loss: When a plain concrete beam is exposed to different temperatures, the water particles within its pores evaporate, resulting in a decrease in weight. The Table 6 below shows the percentage of weight loss in the plain concrete beam after exposure to various temperatures.

Table 6: Summary of Percentage Weight Reduction Plain Concrete Beam

Temperature	C-15		C-25		C-30		C-40	
	4Hr.	8Hr.	4Hr.	8Hr.	4Hr.	8Hr.	4Hr.	8Hr.
20^0C	0	0	0	0	0	0	0	0
100^0C	4	4.34	1.98	1.62	0.77	2.3	1.62	1.6
200^0C	2.43	4.06	1.65	7.37	1.96	6.2	2.38	5.55
300^0C	3.25	3.25	5.2	9.01	3.12	7.87	7.01	6.89

Effect of Temperature Duration on Weight Loss: As the exposure duration increases, the percentage of weight loss generally rises. This can be attributed to the role of aggregates, which constitute over 60% of the concrete's volume and significantly influence the compaction of fresh concrete mixtures.

Relationship between Temperature and Weight Loss Trends: For most concrete beams, except for the low-strength C-15 beam, the percentage of weight loss increases with higher temperatures. This occurs because elevated temperatures enable deeper heat penetration, leading to the evaporation of water molecules and the removal of moisture from internal voids. However, an unexpected trend was observed in the C-15 concrete beam, where the weight loss at 200°C was lower than at 100°C. This anomaly suggests that, at 200°C, certain material properties within the beam may have influenced moisture retention or loss differently than anticipated (24).

Load Carrying Capacity Reduction: When a plain concrete beam is exposed to varying temperatures, its load-carrying capacity decreases. Higher temperatures cause the water particles within the concrete's pores to evaporate, which allows air to enter and results in a loss of strength. The table 7 below illustrates the reduction in the load-carrying capacity of the plain concrete beam after exposure to different temperatures.

Table 7: Summery of Maximum Load Reduction of Plain Concrete Beam

Temperature	C-15		C-25		C-30		C-40	
	4Hr.	8Hr.	4Hr.	8Hr.	4Hr.	8Hr.	4Hr.	8Hr.
20^0C	5.03	5.03	6.268	6.268	7.733	7.733	9.747	9.747
100^0C	3.802	2.875	5.514	5.04	7.192	6.828	9.155	9.144
200^0C	2.746	2.423	3.942	3.306	6.182	5.697	8.143	7.992
300^0C	2.036	1.594	2.111	1.906	5.719	3.974	7.313	6.925

Temperature and Duration Effects: As temperature and exposure duration increase, the residual load-carrying capacity of the plain concrete beam decreases.

Concrete Grade Influence: Higher concrete grades result in a higher residual load-carrying capacity after fire exposure.

In this study, high-strength plain concrete beams C-40 exposed to 300°C for eight hours demonstrated better residual load-carrying capacity than C-25 plain concrete beams under room temperature conditions.

To enhance the practical significance of the findings, it is important to compare the observed results with established code-based predictions and empirical models related to concrete performance under elevated temperatures. According to design guidelines such as Eurocode 2 (EN 1992-1-2) and ACI 216R-14, concrete begins to experience notable strength degradation at temperatures exceeding 300°C, with residual strength dropping to approximately 55–65% of its original value depending on mix type and exposure duration. This closely aligns with the current study, where C-25 concrete lost about 66.33% of its load-carrying capacity after 4 hours at 300°C, as shown in Table 3. Furthermore, codes typically assume linear degradation models, while the current results revealed a more non-linear pattern, particularly in C-15 and C-30 grades, where strength loss accelerated disproportionately with temperature and time. These deviations highlight the influence of concrete mix characteristics and suggest that while design codes offer conservative estimates, they may not fully account for differences in local materials, curing conditions, or moisture content. Incorporating these insights into national codes, particularly in regions like Ethiopia, could enhance the accuracy of fire safety assessments and structural reliability under thermal stress (24).

The overall discussions of the above results are discussed below. Table 1 demonstrates a direct correlation between compressive strength and the maximum load-carrying capacity of plain concrete beams. As the actual compressive strength increases from 12.6 MPa (Group One) to 38.9 MPa (Group Four), the corresponding load-carrying capacity rises from 5.03 kN to 9.747 kN. This trend is clearly visualized in Figure 5, where the load-displacement behavior of concrete beams at room temperature reflects higher peak loads and more extended displacement for higher-strength beams. These results emphasize that concrete's ability to resist bending forces is directly influenced by its inherent compressive strength, supporting prior studies that associate increased density and matrix integrity with better structural resilience under load. Figures 6 through 13 illustrate how elevated temperatures and prolonged exposure durations negatively affect the load-displacement response of C-15, C-25, C-30, and C-40 beams (24). The curves become more compact and the peak load values drop noticeably, indicating degradation of internal cohesion and strength. Tables 2 to 5 further quantify these observations, showing, for example, that C-15 beams experience a load reduction of up to 68.31% at 300°C after eight hours, while C-40 beams exhibit only a 28.95% reduction under the same conditions. These differences highlight the superior thermal resistance of higher-grade concretes. The sharp decline in performance, particularly at 200°C and 300°C, aligns with thermal decomposition stages of concrete, including dehydration of calcium silicate hydrate (C-S-H) gel and the formation of microcracks, as widely reported in literature (23). Table 6 reveals the percentage of weight loss in concrete beams across all grades when subjected to increasing temperatures. The trend generally shows that higher temperatures and longer durations result in more substantial weight loss, particularly due to evaporation of pore water and thermal expansion (23). Interestingly, anomalies such as the C-15 beam at 200°C showing lower weight loss than at 100°C suggest potential experimental variations or internal microstructural influences. Table 7 confirms that as weight loss increases, the maximum load-carrying capacity decreases significantly, reinforcing the notion that thermal exposure weakens the concrete matrix by introducing voids and reducing bond strength. These findings support the hypothesis that temperature not only affects surface characteristics but also deeply impacts the material's internal integrity and load-bearing efficiency (23).

Conclusion

This study investigates the impact of temperature and exposure duration on the load-carrying capacity of plain concrete beams. The experimental findings clearly demonstrate that elevated temperatures, particularly over prolonged durations, significantly reduce the structural integrity of concrete. It was observed that concrete's load-carrying capacity decreases as temperature exposure and duration increase, with variations in performance noted across different concrete grades. Specifically, lower-strength concrete, such as C-15, exhibited more substantial strength reductions compared to higher-strength grades like C-40, which maintained better load-carrying capacity even after extended exposure.

In this study, the C-25 concrete grade, commonly used in Ethiopian structures, was tested. Results showed that a C-25 plain concrete beam exposed to 100°C, 200°C, and 300°C for four hours lost 12.04%, 37.13%, and 66.33% of its load-carrying capacity, respectively. With an additional four hours of exposure, these losses increased to 19.6%, 47.25%, and 69.5%. These findings emphasize that exposure duration has a more significant impact on reducing load-carrying capacity than temperature alone. Prolonged fire exposure accelerates structural failure.

These results highlight the critical need for structural engineers to consider temperature effects in fire safety designs, especially in regions like Ethiopia where fire incidents can lead to severe structural consequences. The study underscores that fire exposure beyond three hours can significantly compromise concrete structures, emphasizing the importance of implementing effective fire resistance measures in building designs. It is recommended that future research consider the simultaneous effects of fire and structural loading to simulate real-world conditions more accurately, and that building codes be updated to include guidelines for enhanced fire resistance, ensuring public safety in the face of potential fire disasters.

To enhance fire resistance in concrete structures, this study recommends incorporating specific fire resistance provisions into Ethiopian building codes, emphasizing the use of higher-grade concrete (e.g., C-30, C-40) for critical elements, and adopting fire-resistant materials and coatings. Future studies should simulate real-world conditions by testing concrete under simultaneous fire exposure and live loads and employing advanced modeling tools for accuracy. Additionally, post-fire structural assessments should guide the safe reuse of buildings, while broader experimental research on reinforced concrete and varying material properties should further inform design practices. Lastly, fire suppression systems and stricter safety regulations are essential to mitigate fire risks and protect structural integrity.

Abbreviations

°C: Degree Celsius (unit of temperature), C-15, C-25, C-30, C-40: Concrete Strength Grades Based on Compressive Strength in MPa, KN: Kilonewton, MPa: Megapascal (unit of pressure or stress), RC: Reinforced Concrete.

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Author Contributions

Tadiyos Nigussie Alemu: Conceptualization of the study, methodology development, data collection, experimental setup, analysis of results, manuscript writing (original draft), final review, Venu Malagavelli: Manuscript review, critical revisions, Cici Jennifer Raj J: Supervision of the research, technical guidance in experimental design, validation of results, Swamy Nadh: Support to the experimental setup, analysis of results, manuscript writing (rough draft), Meron Melaku Aragaw: Assistance in data curation, laboratory work, sample preparation, statistical analysis, and contribution to manuscript writing and review.

Conflict of Interest

The authors declare that there are no financial, professional, or personal conflicts of interest that could have influenced the findings or interpretations of this study. All results and conclusions presented in this paper are based purely on independent research and scientific analysis. All authors have read and approved the final manuscript before submission.

Ethics Approval

This study does not involve human participants, animals, or any sensitive data that would require ethical approval. The experimental procedures followed standard safety and research protocols for structural testing, and no ethical concerns were identified.

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