EUROPEAN JOURNAL OF MATERIALS SCIENCE AND ENGINEERING
Volume 9, Issue 4, 2024: 281-294 | www.ejmse.ro | ISSN: 2537-4338

DOI: 10.36868/ejmse.2024.09.04.281

BEHAVIOR OF CONCRETE UNDER FIRE EXPOSURE

Yisihak GEBRE[1*], Habtom GEBREMARIAM[1], Abrham G. TAREKEGN[1]

[1]School of Civil and Environmental Engineering, Addis Ababa Institute of Technology, Addis Ababa University, Ethiopia.

Abstract

Service structures could be built from different materials and concrete is commonly used in construction due to its beneficial mechanical properties, such as its superior compressive strength, long-lasting durability, and ability to resist fire. Structures are anticipated to withstand the various loads they encounter during their operational lifespan, which can typically be determined based on factors such as the type of service, geographical location, and dimensions. These loads can be accurately modeled using advanced software tools that are continuously evolving. However, fire incidents are difficult to predict, making it challenging to foresee their location, timing, and the extent of their impact on structures, resulting reductions in strength and unexpected stress. Therefore, in this study, to examine the performance of concrete of different strength grades and reinforced concrete (RC) beam specimens exposed to fire at different temperatures, an experimental investigation was carried out. During the test, the maximum duration of fire exposure taken is four hours and maximum concrete surface temperature considered is limited to 246°C. For the RC beams, test was conducted under one-point loading with different specimens of 25 mm and 35 mm concrete covers. The results showed that, the strength of RC beam after fire exposure reduces up to 18% and the compression strength of concrete at 246°C of fire exposure temperature with 25 MPa and 30 MPa were observed to drop by 32%, and 48%, respectively as compared to initial strength. Moreover, comparison of experimental results with numerical models were made. The results revealed that the predicted values of the residual compressive strength proposed by Hertz's model are in good agreement with the experimental values.

Keywords: RC beam, residual strength, fire exposure, temperature.

Introduction

Various construction materials used for structural members possess different capacities for resisting fire. Concrete offers an advantage over other building materials due to its intrinsic fire-resistant properties. Moreover, concrete buildings have good behavior under heat/fire attack due to its low conductivity [1]. Concrete under fire exposure undergoes significant changes in its mechanical properties due to the high temperatures involved. This exposure can lead to a reduction in compressive strength and structural integrity, posing challenges for its use in fire-resistant structures. Understanding these changes is crucial for designing resilient and safe infrastructure in fire-prone environments [2-5].

It is essential to design concrete structures with consideration for fire effects [4]. When considering the potential loss of life and resources in fire accidents, prioritizing the implementation of fire safety measures and achieving desired fire resistance ratings in design is paramount. In fire design, the "factor of safety" is contained within the fire resistance rating. Therefore, in a given scenario, a member with a four-hour resistance rating would inherently

*Corresponding author: yisgeb2004@gmail.com

possess a higher "factor of safety" compared to one with a two-hour resistance rating [6]. Hence, the higher the resistance rating, the longer the member can withstand elevated temperatures without experiencing substantial strength deterioration.

Effect of Elevated Temperature on Concrete Strength

The effect of elevated temperature on concrete strength is a critical aspect of structural fire safety. At high temperatures, the properties of concrete undergo significant changes due to thermal expansion, dehydration of cement paste, and degradation of the constituent materials, especially the aggregates [7-10]. These changes lead to a reduction in mechanical properties of concrete, thereby compromising the structural integrity of buildings and infrastructure during fire incidents. Due to the increased temperature and water evaporation, cement hydration is accelerated through internal autoclaving when temperatures reach approximately 300°C [7]. At high temperatures, the compressive strength of concrete decreases due to thermal imbalances among its ingredients. The hardened paste and aggregates expand and shrink at various temperatures [8, 9].

The extent of compressive strength deterioration in concrete notably varies depending on the type of aggregate used. As stated in [11], concrete samples of three grades - M25, M30, and M35 were exposed to temperatures of 300°C, 600°C, and 900°C for one hour and then tested. The findings revealed a reduction in compression strength ranging from 10.9% to 76.5% during sudden water cooling, and from 19.4% to 82% during progressive cooling in the air.

A related study on effects of temperature on concretes demonstrated that the residual compressive strength of high-strength concrete mixed with blended cement, after being heated to 800 °C and water-quenched, was 31% of its initial strength. In comparison, the corresponding residual strength of concrete made with ordinary Portland cement was obtained as 44% [12].

The study by [13] showed that the compressive strength of high-strength concrete decreased notably with increasing temperatures. When concrete exposed to a fire flame at 400°C followed by a sudden water cooling, the residual strength ranged from 71% to 89% of its initial strength. With a temperature increase to 600°C, the residual strength of concrete varied from 46% to 81% of its initial strength. It was also studied that after being exposed to a fire flame at 850°C, the residual strength of concrete ranged from 29% to 45%. Moreover, the researcher developed a relation between the compressive strength and the fire flame temperature for 30, 60 and 90 days [13]. The study by [14] is focused to examine the compressive strength of concrete subjected to drying at elevated temperatures. Findings indicated an initial decrease followed by an increase in compressive strength as moisture content decreased. Moreover, the moisture content associated with the minimum strength reduced as temperature increased, and for concrete with equivalent moisture content, compressive strength decreased as heating temperature increased.

In reinforced concrete beams, the mechanical properties of the reinforcing bars such as ultimate strength, yield strength, and modulus of elasticity decrease as temperature increases [15]. Consequently, their bending and shear capacities are also reduced accordingly. The experiment conducted by [16] investigated the effects of fire on the strength of RC structural members. Samples were subjected to burning in a fire, with cooling carried out using water splashing, CO_2 powder fire extinguisher, and air-cooling methods. The results revealed that different cooling methods induced varying degrees of deterioration and significant effects on the properties of concrete. Residual strength varied from 37.73% to 86.67%.

To examine the effect of changing concrete cover, A.A. Mohamed, et al. [1] investigated three beams with concrete covers of 40 mm, 50 mm, and 60 mm. Results indicated that increasing the concrete cover by 20% and 50% reduced the temperature of the reinforcing steel bars by approximately 12% and 24%, respectively, under the same fire exposure conditions.

On the other hand, R.K. Aboud, et al. [17] investigated the effect of fire exposure on the properties of self-compacting concrete reinforced by glass fibers. The adopted fire exposure involved temperatures ranging from 300°C to 800°C for one hour, followed by sudden cooling. Glass fiber volume fractions of 0%, 0.5%, 1%, and 1.5% were examined. The effect of fire exposure showed an inverse relationship with different fiber content at temperatures between 300°C and 700°C, while at 800°C, the reduction in mechanical properties was more pronounced for specimens with 1.5% fiber content.

Effect of Fire to Concrete Strength

B. Topçu and I. Ikdag [18] examined the impact of fire exposure duration and the thickness of concrete cover on the behavior of the shear zone in reinforced concrete (RC) beams exposed to fire and subsequently cooled by water. Their findings indicated that thin concrete covers and extended exposure times significantly influence the strength of both the concrete and reinforcing steel. The research conducted by D.P. Thanaraj et al. [19] investigated that the ultimate load of M20 grade reinforced concrete beams exposed to fire for durations of 15, 30, 60, and 240 minutes. They found that the ultimate load decreased by approximately 22%, 29%, 56%, and 75%, respectively. Similarly, for M50 grade beams exposed to fire for the same durations, the ultimate load reductions were approximately 11%, 1.1%, 34%, and 71%, respectively. However, during fire exposure of lasting up to 60 minutes, the load-deflection response of M20 grade reinforced concrete beams exhibited no yield point, but rather plastic deformation until failure was recorded [19]. D. K.Sudarshan and A.K. Vyas [20] studied the effect of fire on the compressive strength of concrete exposed to fire in a temperature range of 200°C - 800°C. A decrease of about 4%-5% in strength was observed at an exposure temperature of 200°C. Moreover, cracks started on the surface of concrete specimens at 600°C due to pore pressure built up by conversion of moisture into vapors.

Previous research has mainly focused on investigating the effects of fire exposure on concrete properties. However, the duration of fire exposure for various concrete grades has been studied to a limited extent. In this study, an experimental investigation was carried out to examine the performance of concrete and reinforced concrete (RC) beam specimens of various concrete grades and concrete cover exposed to fire at different temperature and duration.

The experimental findings of the current study is compared with test results of the residual compressive strength of concrete investigated by different studies and the numerical models that were proposed by researchers, along with Eurocode 2.

Numerical Modeling of Concrete with Fire Exposure

There are several empirical formulas and mathematical models proposed by researchers which correlate the residual compressive strength of concrete with fire exposure temperature.

i) *M. Mohammad et al.* [13]:

$$\boldsymbol{f_{cua}} = e^{(0.03251\boldsymbol{f_{cub}} - 0.00036Age - 0.00096T - 0.00024\rho + 2.886)} \qquad (1)$$

where f_{cub} and f_{cua} are compressive strength of concrete before and after exposure to fire, respectively (MPa), Age is age of the specimens at the time of exposure (days), T is temperature of fire flame (°C) and ρ is density of concrete after exposure to fire flame (kg/m^3).

ii) *K. D. Hertz* [21]:

$$\boldsymbol{f_{c,T}} = \boldsymbol{f_c}\left(\frac{1}{1 + (T/10^4) + (T/780)^2 + (T/490)^8 + (T/10^5)^{64}}\right) \qquad (2)$$

where $f_{c,T}$ is the residual compressive strength after exposure to fire in MPa, f_c is the initial compressive strength in MPa, and T is the temperature attained during the fire in °C.

iii) Eurocode 2: EN 1992-1-2 [22]:

The strength characteristics of uniaxially stressed concrete at elevated temperatures are determined based on the stress-strain relationships for normal weight concrete outlined in Table 3.1 of the code.

Materials and Methods

Materials

Cement: - The cementitious materials used for making the concrete mixtures were Ordinary Portland cement (CEM I-42.5 R).

Coarse Aggregates: - In this study, different-sized crushed stones (2-8 mm, 8-16 mm, and 16–20 mm) were used as coarse aggregates. To get the required gradation of aggregates, samples are crushed and sieved according to ASTM C 136-06 [23].

Fine Aggregates: - Natural River sand with a particle size of less than 2 mm was used as fine aggregate. It was ensured that the fine aggregate was dirt-free, inactive, and free from natural issues, clay, and silt.

Reinforcing Bars: - Longitudinal bars of diameter 8 mm (yield strength 496.03MPa) and stirrups of diameter 6 mm (yield strength 381.26MPa) were used.

Mix Design

The material proportions are determined using a volume-based approach. Cement, sand and coarse aggregate mix proportion is given in the following Table 1. Two groups of concrete mix design were prepared, with target compressive strengths of 25 MPa (Group 1) and 30 MPa (Group 2).

Table 1. Concrete mix design

No.	Mix design	Quantity (kg/m^3)		Bulk Density
		Group 1	Group 2	
1	Cement OPC	360	400	3.15
2	Water	162	185	1.00
3	Fine aggregate	740	620	2.70
4	Coarse aggregate	1005	1360	2.80

The 28th days compressive strength of concrete found to be 24.75MPa and 46.15MPa for Groups 1 and 2 specimens, respectively.

Specimen Preparation

In this study, a total of 42 concrete cube specimen with dimension of 150 mm were produced, 21 for each group of specimens. Testing procedures for measuring the compressive strength of concrete is conducted in accordance with EN 12390-4:2019 standard [24]. Furthermore, a total of 24 reinforced concrete beams with 250 ×150 mm (h × b) with an overall length of 1000 mm were prepared. Two diameter 8mm deformed bars at the top and three diameter 8mm deformed bars at bottom surfaces were provided. Stirrups were made of diameter 6 mm bars spaced at 200 mm, with 15 and 25mm concrete covers. The longitudinal and cross-section of the test beam is shown in Fig. 1. The beam’s capacity was checked and it is expected to resist a maximum moment capacity of 27.33 kN-m, shear capacity 54.67 kN with deflection of 1.90 mm at mid span.

Specimen Notation and Designation

Concrete sample specimens are designated as follows: CM1-0 is the control mix for Group one concrete cubes that has not been burned in a fire, CT1-1-3 is the concrete in Group 1 that has been burned at 100°C for exposure duration of 3hrs, CT1-2-4 is for 200°C exposed for 4hrs and etc. For Group-2 specimens, the third term is 2. Furthermore, reinforced concrete beam specimens (with 15mm concrete cover) that have not been burned in a fire are labeled as CB1-0, whereas reinforced concrete beams that have been burned at 100°C for 2hrs are designated as BT1-1-2, concrete beam burnt at 200°C for four hours is specified as BT1-2-4, and so on. Similarly, for RC beams with a 25mm concrete cover, the third term is designated as 2.

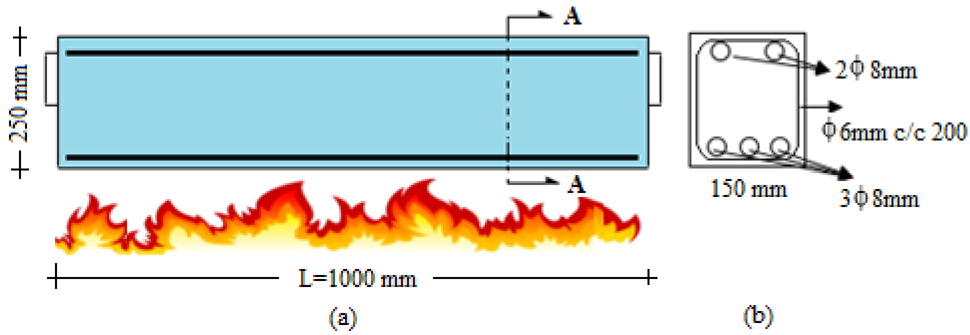


Fig. 1. a) Longitudinal section of sample RC beams; b) section A-A

Burning Procedures

Tires were chosen to facilitate and increase the burning process because of their ability to burn for extended periods of time. The concrete burning technique involves placing a steel grill on a flat slope, positioning combustible waste tires behind it, starting the fire, and managing it to achieve and maintain the required temperature on the concrete surface. Samples were burned for desired periods ranging from two to four hours at various target concrete surface temperatures ranging from 100°C up to 300°C. To manage the temperature of the concrete surface, the fire is adjusted by adding fuel and, if necessary, lowering its burning with water to attain the desired temperature. The temperature readings during the burning process are expressed with an accuracy of ±5°C. Finally, the specimens are allowed to withdraw after three to four hours of cooling before being tested. Tests were conducted after a one-day cooling time of burnt specimens at ambient temperature. Figs. 2 and 3 depict the course of the burning process up to the testing stage.

Fig. 2. Initial burning stage

Fig. 3. Infrared thermometer

Concrete cube samples

Figs. 4 and 5 show the concrete cube samples: Fig. 4 shows burnt and cooled concrete cubes, while Fig. 5 illustrates excessive burning of a concrete cube.

Fig. 4. Burnt and cooled concrete cubes

Fig. 5. Excessive burning of concrete cube

Unrestrained Reinforced Concrete Beams

Fig. 6 below illustrates the intensified fire conditions created during the burning of the reinforced concrete beams.

Fig. 6. RC beams under intensified burning

Experimental Setup

The beam specimen was simply supported with a single point load applied to the mid-span, and deflection was measured using a linear variable displacement transducer (LVDT). The span of the beam is 750mm and it is simply supported. Figs. 7 and 8 show the experimental setup for the cube and RC beam specimens, respectively.

Results and Discussion

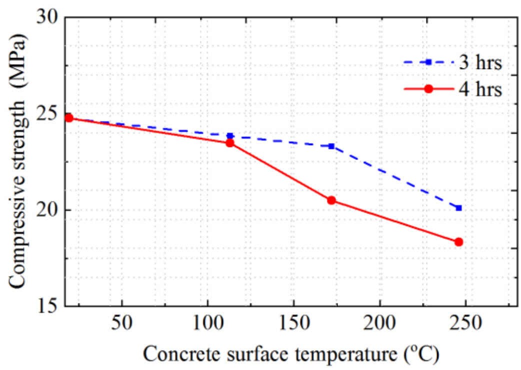
Concrete Cubes

Experimental test results

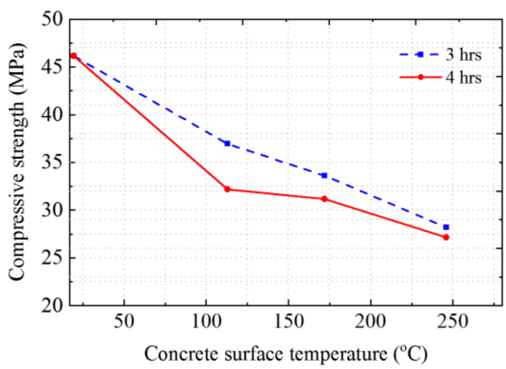
Residual compressive strength versus concrete surface temperature in the duration of fire exposure for Group 1 and 2 concrete cube specimens are plotted in Figs. 9 (a) and (b), respectively. As shown in Fig. 9 (a), for Group 1 concrete cube specimens, a concrete surface temperature of 246°C, burnt for four hours, resulted in a reduction of compressive strength by 25.9%. Additionally, concrete exposed to fire at the same temperature for four hours exhibited a reduction in compressive strength of 41.2% for Group 2 specimens, as illustrated in Fig. 9(b). These reductions indicate that the duration of fire exposure is a crucial factor influencing the residual compressive strength following fire exposure. The experimental result of the current study is in good agreement with research conducted by C. Rao and R. Kumar [25], in which at elevated temperatures, the strength of concrete was found to be dropped by 7.4% - 43.5%. Additionally, studies conducted by [26-28] have demonstrated that the decrease in strength at higher temperatures becomes more pronounced with increasing concrete grades.

Fig. 7. Test setup for compression test

Fig. 8. Test setup with one-point loading



(a)



(b)

Fig. 9. Residual compressive strength versus concrete surface temperature
(a) Group 1 and (b) Group 2 concrete specimens

It is also observed in Figs. 9 (a) and (b) that as a concrete surface temperature increase, the corresponding compressive strength of concrete decreases and these show higher temperatures bring about larger reduction in compressive strength. Throughout the experiment, it was noted that excessive exposure of the concrete to fire resulted in the disintegration of the bonding between cement paste and coarse particles, in the worst-case, the concrete could be easily scratched by fingernails.

Comparison of numerical models and experimental results

Comparison of test results of compressive strength of concrete with prediction models are shown in Tables 2 and 3. Moreover, Tables 2 and 3 are combined and the comparison results are shown in Fig 10.

Table 2. Compressive strength - Group 1 (experimental and predicted values)

Notation	T (°C)	Compressive strength (MPa)				Ratio		
		Test results (1)	Eqn. 1 (2)	Eqn. 2 (3)	Eurocode 2 (4)	(2)/(1)	(3)/(1)	(4)/(1)
CM1-0	19.5	24.75	22.36	26.50	24.75	0.90	1.07	1.00
CT1-1.3	113	22.85	20.51	23.84	26.85	0.90	1.04	1.18
CT1-1.4	113	23.83	21.07	23.84	26.85	0.88	1.00	1.13
CT1-2.3	172	23.29	20.04	22.14	26.06	0.86	0.95	1.12
CT1-2.4	172	21.50	20.12	22.14	26.06	0.94	1.03	1.21
CT1-3.3	246	20.10	19.22	20.03	25.06	0.96	1.00	1.25
CT1-3.4	246	18.34	19.27	20.03	25.06	1.05	1.09	1.37

Table 3. Compressive strength – Group 2 (experimental and predicted values)

Notation	T (°C)	Compressive strength (MPa)				Ratio		
		Test results (1)	Eqn. 1 (2)	Eqn. 2 (3)	Eurocode 2 (4)	(2)/(1)	(3)/(1)	(4)/(1)
CM2-0	19.5	46.15	45.06	44.78	46.15	0.98	0.97	1.00
CT2-1.3	113	36.94	30.63	38.62	42.76	0.83	1.05	1.16
CT2-1.4	113	32.17	26.83	38.62	42.76	0.83	1.20	1.33
CT2-2.3	172	33.59	26.75	35.14	38.49	0.80	1.05	1.15
CT2-2.4	172	31.17	24.77	35.14	38.49	0.79	1.13	1.23
CT2-3.3	246	28.2	21.53	31.14	32.78	0.76	1.10	1.16
CT2-3.4	246	27.15	20.85	31.14	32.78	0.77	1.15	1.21

As shown in Tables 2, 3, and Fig. 10, the variation in the predicted residual compressive strength of concrete calculated using Equation (1) [13] compared to the corresponding experimental values are ranging from 4% to 12% for Group 1 and 2% to 23% for Group 2 specimens. Moreover, experimental measurements and the estimated compressive strength of concrete using Equation (2) [21] differ by 3% to 7% and 3% to 20% for Group 1 and 2, respectively. However, the compressive strength of concrete estimated using Eurocode 2 [22] varies significantly higher than the experimental results. The results also showed that the prediction model proposed by K. D. Hertz [21] is in good agreement with the experimental results and is appropriate for predicting the residual compressive strength of concrete under fire exposure. M. Mohammad et al.'s prediction model was found conservative, particularly for concrete with a high parent compressive strength.

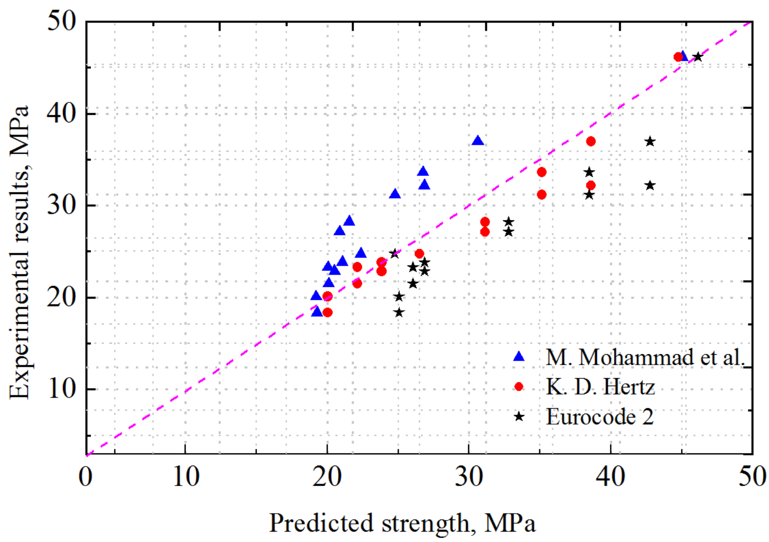


Fig. 10. Comparison of numerical models and experimental results

Comparison of the present study with various literatures

In this section, the experimental results of the present study are compared with previous studies. The comparisons are summarized in Table 4, focusing the present study on Group 1 concrete specimens for an exposure duration of 4hr and exclusively on the concrete's residual compressive strength.

Table 4. Comparison of residual compressive strength

	J. Shen, and Q. Xu [14]		D.k. Sudarshan, et al. [20]		G.A. Khoury [29]		Present study	
Tempreture (°C)	**Compressive Strength (MPa)**	**Change (%)**	**Compressive Strength (MPa)**	**Change (%)**	**Compressive Strength (MPa)**	**Change (%)**	**Compressive Strength (MPa)**	**Change (%)**
19.5	65.24	-	32.93	-	54.2		24.75	-
113	61.93	-5.07			56.7	4.61	23.83	-3.71
200	59.31	-9.09	28.07	-14.76	59.8	10.33	21.50	-13.13
246	52.27	-19.88			45.62	-15.83	18.34	-25.89
400			27.47	-16.59	38.47	-29.02		

As shown in Table 4, the results of previous research [14, 20] indicate that the residual compressive strength of concrete decreases as temperature increases, and this trend is comparable to the findings of the current study. However, a study by G.A. Khoury [29] shows an increase in compressive strength at temperatures of 100 °C and 200 °C compared to the control mix.

Unrestrained Reinforced Concrete Beams

Tables 5 and 6 show test results of RC beam specimens under different fire exposures and concrete covers. The scatter plot of failure load versus exposure duration and temperature with mid-span deflection for RC beam samples with 15 mm and 25 mm concrete covers are shown in Figs. 11 and 12, respectively. Values on the graph denote the ultimate capacity of the beams.

Table 5. RC beam samples with 15 mm concrete cover

Notation	Target Temp. (°C)	Actual Temp. (°C)	exposure duration (hr.)	Failure load (kN)	Mid span deflection (mm)	Reduction in ultimate load capacity (%)	Increment in deflection (%)
CB1-0	20	19.5	0	104.4	7.08	-	-
BT1-1-2	100	113	2	99.1	12.01	5.08	69.63
BT1-1-3	100	113	3	97.6	17.62	6.51	148.87
BT1-1-4	100	113	4	88.8	21.49	14.94	203.53
BT1-2-2	200	172	2	94.1	14.36	9.87	102.82
BT1-2-3	200	172	3	86.9	16.15	16.76	128.11
BT1-2-4	200	172	4	92.7	19.72	11.21	178.53
BT1-3-2	300	246	2	97.5	18.91	6.61	167.09
BT1-3-3	300	246	3	82.9	22.23	20.59	213.98
BT1-3-4	300	246	4	85.4	25.47	18.20	259.75

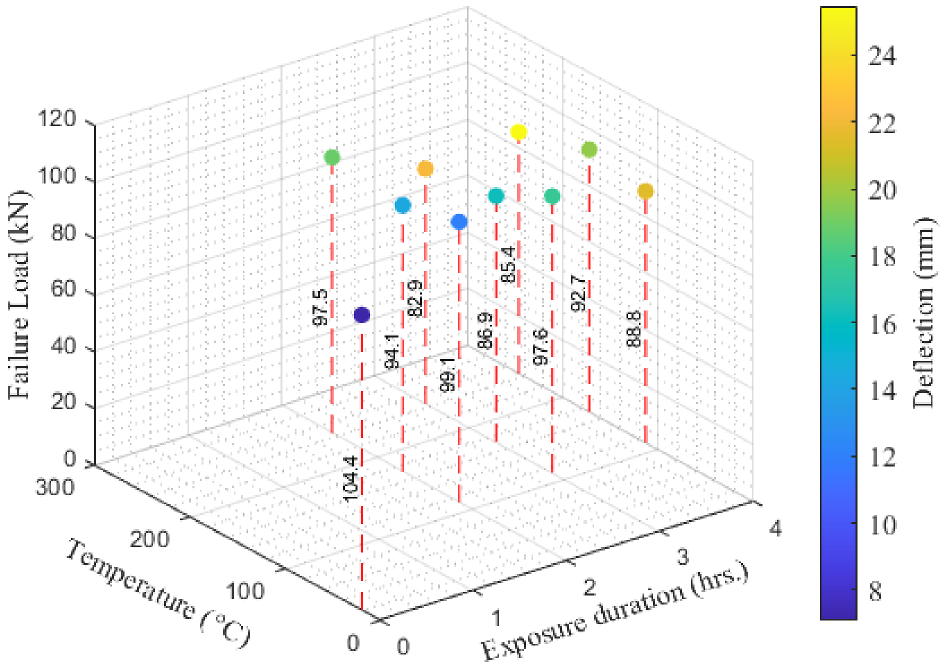


Fig. 11. Failure load vs. exposure duration and temperature with deflection (15 mm cover)

Table 6. RC beam samples with 25 mm concrete cover

Notation	Target Temp. (°C)	Actual Temp. (°C)	exposure duration (hr.)	Failure load (kN)	Mid span deflection (mm)	Reduction in ultimate load capacity (%)	Increment in deflection (%)
CB2-0	20	19.5	0	97.8	6.74	-	-
BT2-1-2	100	113	2	96.4	11.95	1.34	77.3
BT2-1-3	100	113	3	90.2	16.12	7.28	139.2
BT2-1-4	100	113	4	89.2	19.01	8.79	182.0
BT2-2-2	200	172	2	92.1	13.02	5.46	93.2
BT2-2-3	200	172	3	98.7	19.47	-0.86	188.9
BT2-2-4	200	172	4	90.2	22.26	7.28	230.3

Notation	Target Temp. (°C)	Actual Temp. (°C)	exposure duration (hr.)	Failure load (kN)	Mid span deflection (mm)	Reduction in ultimate load capacity (%)	Increment in deflection (%)
BT2-3-2	300	246	2	95.1	16.97	2.59	151.8
BT2-3-3	300	246	3	94.4	17.05	3.26	153.0
BT2-3-4	300	246	4	90.3	19.94	7.18	195.8

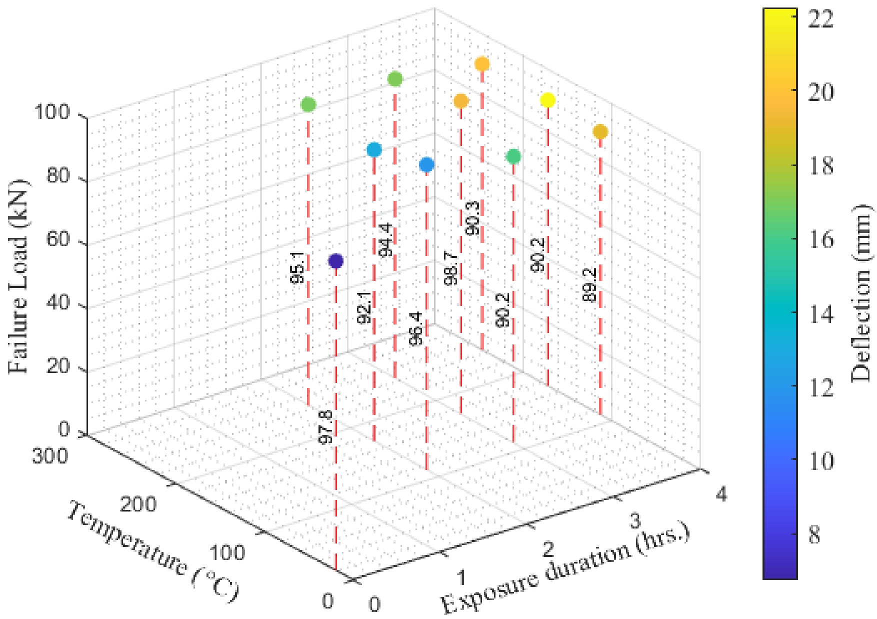


Fig. 12. Failure load vs. exposure duration and temperature with deflection (25 mm cover)

As observed in Table 5, a concrete surface temperature of 246°C sustained for 3hrs of a RC beam with concrete cover of 15 mm yielded a maximum reduction in ultimate load capacity of 20.59% (BT1-3-3) with a remarkable increment in deflection of 213.98% as compared to the control beam (CB1-0). Table 6 shows that with a 25mm concrete cover, the maximum reduction in load capacity was observed at a surface temperature of 100°C sustained for 4 hours (BT2-1-4). This result is consistent with D. N. Bilow, [30], who discovered that at higher temperatures and exposure times, concrete cover had an effect on the performance of reinforced concrete members. It is also observed that adding a 10mm concrete cover to the beam (BT1-3-4) improves its fire resistance and reduces deflection by 23.22% (from 25.45mm to 19.94mm).

Conclusions

In this study, tests were conducted to investigate the effects of concrete and RC beams exposed to a maximum fire exposure of 246°C for different durations From the experimental results, the following conclusions are made:

The mix proportion has a major effect on the concrete's residual compressive strength after being exposed to fire. It is also showed that the percentage loss in compressive strength is higher for concretes with higher strengths than for those with lower strengths; for example, at maximum fire exposure and duration, Group 1 and Group 2 specimens lost their compressive strength by 25.9% and 41.7%, respectively.

The mechanical characteristics of concrete decrease with increasing temperature. The decrease becomes particularly significant when the temperature is between 172°C and 246°C.

Concrete cover variation was found to be a significant factor to improve the ultimate load carrying capacity of RC beams exposed to fire. It is observed that increasing the concrete cover by 10 mm (from 15 mm to 25 mm) enhances the load capacity by 5.42% (from 85.4 kN to 90.3 kN) for maximum fire exposure and duration (BT1-3-4 and BT2-3-4). Similarly, a 23.22% (from 25.45mm to 19.94mm) reduction in deflection was obtained.

The experimental results of the compressive strength of concrete were found to be consistent with code predictions of K. D. Hertz's model. Furthermore, the reduction in residual compressive strength obtained by J. Shen and Q. Xu shows a similar trend to the current study.

Future Directions and Limitations

This study was limited to examining the effect of fire on concrete properties, using CEM I-42.5 R cement type and a maximum aggregate size of 20 mm. In the future, it is recommended that the effect of aggregate size, cement type and admixture on fire performance of RC members should be taken into account. Furthermore, the reinforcing bars be covered adequately to prevent from being in direct contact with fire.

Acknowledgement

Tests were conducted in "Addis Ababa University, Addis Ababa Institute of Technology (AAiT), School of Civil and Environmental Engineering, Materials Testing Laboratory", which is highly acknowledged by the authors.

References

[1] A.A. Mohamed, M.S. Issa, and A.A. Mahmoud, *Behavior of Reinforced Concrete Beams Exposed to Fire*,**Engineering Research Journal (Shoubra),** 47(1), 2021, pp.139-149.

[2] W.C. Jau, K.L. Huang, *A study of reinforced concrete corner columns after fire*, **Cement Concrete Composite 30 (7),** 2008, 622–638.

[3] N. Anand, G.P. Arulraj, *Effect of grade of concrete on the performance of self compacting concrete beams subjected to elevated temperatures*, **Fire Technology 50**, 2014, pp.1269-1284.

[4] K. Behfarnia, M. Shahbaz, *The effect of elevated temperature on the residual tensile strength and physical properties of the alkali-activated slag concrete*, **Journal of Building Engineering**, **20**, 2018, pp. 442–454.

[5] N. Anand, A. Godwin, *Influence of mineral admixtures on mechanical properties of self-compacting concrete under elevated temperature*, **Fire Materials 7 (40)**, 2016, pp. 940–958.

[6] *Guide for Determining the Fire Endurance of Concrete Elements*, **American Concrete Institute Committee** 216, ACI 216 R-89, 1994.

[7] O. Arioz, *Effects of elevated temperatures on properties of concrete*, **Fire safety journal**, **42**, 2007, pp. 516–522.

[8] C.S. Poon, S. Azhar, M. Anson, Y.L. Wong, *Strength and durability recovery of fire damaged concrete after post-fire-curing*, **Cement and Concrete Research 31**, 2001, pp. 1307-1318.

[9] D.P. Thanaraj, N. Anand, P. Arulraj, *Experimental investigation of mechanical properties and physical characteristics of concrete under standard fire exposure*, **Journal of Engineering, Design and Technology 17 (5)**, 2019, pp. 878–903.

[10] A. Varghese, D. J. Samuel, N. Anand, G. P. Arulraj, *Studies on behavior of fire affected fiber reinforced concrete*, **Int. J. Civ. Eng. Technology 9 (10)**, 2018, pp. 1668–1675.

[11] A.M. Lafta, H.K. Sultan, A.J. Abdulkareem, and A.A. Hassan, *Effect of the heat from fire on the strength of the concrete*. **In AIP Conference Proceedings, 2806 (1),** 2023, pp 1-6.

[12] V. Kodur and W. Khaliq, *Effect of temperature on thermal properties of different types of high strength concrete*, **Journal of Materials in Civil Engineering, 23(6)**, 2011**,** pp. 793-801.

[13] M. Mohammad, S. A. Saif Ali, A. A. Ali, *Mathematical Models for Prediction of Some Mechanical Properties of Concrete Exposed to Burning*, **University of Babylon Repository,** 2011.

[14] J. Shen, and Q. Xu, *Effect of elevated temperatures on compressive strength of concrete*, **Construction and Building Materials,** *229*, 2019, p.116846.

[15] E. Ünlüoglu, I.B. Topçu, B. Yalaman, *Concrete cover effect on reinforced concrete bars exposed to high temperatures*, **Construction and Building Materials, 21 (6)**, 2007, pp. 1155-1160.

[16] L.O. Onundi, M.B. Oumarou, and A.M. Alkali, *Effects of fire on the strength of reinforced concrete structural members*, **American Journal of Civil Engineering and Architecture**, ***7*(1),** 2019, pp.1-12.

[17] R.K. Aboud, h.K. Awad, and S.D. Mohammed, *Effect of Fire Exposure on the Properties of Self-Compacting Concrete reinforced by Glass Fibers*, **Engineering, Technology & Applied Science Research, 14(2),** 2024, pp.13369-13375.

[18] I.B. Topçu, B. Is¸Ikdag, *The effect of cover thickness on rebars exposed to elevated temperatures*, **Construction and Building Materials, 22 (10)**, 2008, pp. 2053-2058.

[19] D.P. Thanaraj, N. Anand, P Arulraj, K Al-Jabri, *Investigation on structural and thermal performance of reinforced concrete beams exposed to standard fire*, **Journal of Building Engineering, 32**, 2020, p.101764.

[20] D.K. Sudarshan, and A.K. Vyas, *Impact of fire on mechanical properties of concrete containing marble waste*, **Journal of King Saud University-Engineering Sciences, 31(1),** 2019, pp.42-51.

[21] K. D. Hertz, *Concrete strength for fire safety design*, **Magazine of Concrete Research, 57 (8)**, 2005, pp. 445–453.

[22] EN 1992-1-2: Eurocode 2: *Design of Concrete Structures-Part 1-2: General Rules-Structural Fire Design*, Brussels, Belgium, 2004.

[23] ASTM C 136-06: *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*, **ASTM International,** 2014.

[24] EN 12390-4:2019, *Testing hardened concrete - Part 4: Compressive strength of test specimens*, 2019.

[25] C. Rao, R. Kumar, *A study on behaviour of normal strength concrete and high strength concrete subjected to elevated temperatures*, **International Journal of Civil and Environmental Engineering, 9 (3)**, 2015, pp. 283-287.

[26] B. Toumi, M. Resheidat, Z. Guemmadi, *Coupled effect of high temperature and heating time on the residual strength of normal and high-strength concretes*, **Jordan Journal of Civil Engineering, 3(4)**, 2009, pp. 322-330.

[27] K. K. Poloju, R.K Manchiryal, C. Rahul, *Strength Studies on Different Grades of Concrete Considering Fire Exposure*, **American Journal of Civil Engineering**, **6(1)**, 2018, pp. 16-23.

[28] D Larissa, A. L Kirchhof, P Luiz Carlos, F Silva, *Assessment of Concrete Residual Strength at High Temperatures using Ultrasonic Pulse Velocity,* **The e-journal of non-destructive testing 20(7)**, 2015, pp. 1-9.

[29] G.A. Khoury, *Effect of fire on concrete and concrete structures,* **Progress in Structural Engineering and Materials, 2(4),** 2000, pp.429-447.

[30] D. N. Bilow, and M. E. Kamara, *Fire and concrete structures,* **In Structures Congress: Crossing Borders**, 2008, pp. 1-10.

Received: March 24, 2024
Accepted: July 01, 2024