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Behavior of reinforced self-curing concrete slabs exposed to fire

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Noha Yehia Elwakkad [1]

Keywords

Fire, Self-curing concrete, Superplasticizer, Fly Ash, Flat slabs, Reinforcement ratio.

Abstract

The influence of fire on self-curing reinforced concrete flat slabs was inspected in this study. In this paper the focus will be on the effectiveness of the reinforcement ratio, heat duration and cooling method on the behavior of self-curing (SCU) reinforced concrete flat slabs exposed to fire. To create SCU concrete, polyethylene glycol (PEG 400) is added at a rate of 0.5% of cement weight. Twenty-five RC plates (1200 mm x 1200 mm x 70 mm) lying on four supports and being subjected to concentrated load were used to achieve the experimental programmed. The experimental program was conducted in two stages. The first stage, the specimen exposed to high temperature (600^{o}c) for 1 hour and 2 hours. To record the failure load and the deflections at each load increment, the load was gradually increased in the second stage. The results show that the cracking and the ultimate loads decreased, while the deflection increased either with the increase of fire flame duration and cooling method from gradually to sudden.

1. Introduction

Reinforced concrete (RC) slab floors have taken many different forms. They are classed in a variety of ways, but the most frequent classification is based on the structural actions of the slabs. A flat slab is a form of reinforced concrete floor structure that is widely and commonly used.

When designing RC slabs for fire resistance, prescriptive generic ratings that outline the minimal slab dimensions and concrete covering for reinforcing bars are frequently employed .These fire resistance design parameters are based on standard fire tests. The design methodologies for RC slabs exposed to fire depend on the support conditions of the slabs. Several studies [1-5] summarize the building codes' guidelines for slab design considering fire exposure and rational design approaches. Most national building codes include a need for slab fire resistance ratings as a general requirement. Wade (1991) [6] summarized the standard fire resistance ratings for RC columns, beams, and slabs. Table 1 details the requirements for minimum coverings and minimum dimensions for fire resistance ratings ranging from 0.5 up to four hours for reinforced concrete slabs.

[1] 54 Abu-Elfadl Street, Tanta, Egypt

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Table 1: Fire resistance ratings of RC slabs (data from Wade (1991)) [6]

Fire-resistance Rating	Thickness/Cover (mm)						Notes
	0.5 hour	1 hour	1.5 hours	2 hours	3 hours	4 hours	
Document, standard or code							
MP9:1989 (NZ)	60/15	80/20	100/20	120/20	150/23	175/25	Simply supported
BS8110:1085 (UK)	75/15	95/20	110/25	125/35	150/45	170/55	simply supported, Dense aggregate, plain soffit
BRE:1998 (UK)	75/15	95/20	110/25	125/35	150/45	175/55	simply supported, Dense aggregate, plain soffit, effective cover
FIP/CEB:1975 (EUR)	60/10	80/20	100/30	120/40	150/55	175/65	simply supported, Dense aggregate, one-way span, critical temperature = 550 ^oC
CEB:1987 (EUR)	60/10	80/25	100/35	120/45	150/60	175/70	simply supported, Dense aggregate, one-way span, critical temperature = 550 ^oC, cover to steel axis
UBC:1988 (USA)	-/-	89/19	-/-	127/25	157/25	-/32	Siliceous aggregate
AS 3600:1988 (AUS)	60/15	80/20	100/25	120/30	150/45	170/55	One-way simply supported

Several researchers studied the influence of fire on the behavior of RC slabs [7-36]. El-Fitiany and Youssef [7] studied the interaction diagram of reinforced concrete columns that had been exposed to fire and concluded that there is a necessary need for new tools to evaluate the performance of heated RC elements under fire. This is in light of the movement of all codes toward designing the reinforced concrete elements under fire-based circumstances. According to Khouri [8], in order to achieve fire-resistance for materials, heat transfer in an element must be kept within the permissible limits across the whole section, and the rebar must be covered with concrete to keep the steel temperature lower than the peak values for the required fire resistance period to be gained. Caetano [9] shows that after any accident, the building must be inspected to determine the possibility of repair and rehabilitation. One of the requirements for a structural RC element to be safe is the presence of a minimum bond between them.

Karim [10] studied the behavior of solid slab exposed to the fire flame. Twenty-four RC slab were casted and tested with dimension (60 cm × 60 cm × 4 cm), the values of the compressive strength (Fcu) ranged from 30 to 38 MPa, and with reinforcement ratios (ρ) 0.00492 and 0.00875. Sixteen reinforced concrete plates have been subjected to elevated temperatures from 400 up to 600 °C for an hour. The specimens have been cooled gradually, after that the specimens have been tested under distributed loads. The results show that the failure load capacity of RC specimens has been decreased with rising fire temperatures. The slab specimens with a greater reinforcement ratio ρ and exposed to 600 °C showed the greatest reduction. At 600 °C, the remaining load capacity of the tested specimens ranges from (84.2-86%) for RC slab specimens of group (A) reinforced with ρ of (0.00875, 0.00492), and from (83.7-85%) for tested slabs of group (B) reinforced with the same ρ. after the RC slab specimens have been exposed to fire, they are capable of withstanding the service load, however with a lowering factor of safety. The results have shown that there is more reduction in the results after the specimens were exposed to elevated temperature compared with the reference specimens. Prasad [11] investigated the thermal behavior of the RC slabs exposed to fire. The RCC slabs (3300 mm ×1200 mm × 200 mm) were modelled in ANSYS 14.5 to demonstrate slab behavior at high temperatures with concrete grades M25, M70, and M100 with covers of 30mm, 40mm, and 50mm. load-deflection curves have been studied, and the percentage of deflection with and without heat. In the first stage, nine specimens have been cast to show the influence of using various grades of concrete mixtures with different cover thickness. The heat has been applied on the principle of ISO 834 curve. The results showed that slab deflection reduces as the amount of cover given rises. When the grade of concrete was increased, the deflection of the tested specimens was decreased. The results have been obtained that the analysis has demonstrated that the minimum deflection for M100 with cover 50mm.

In 2016, Ghanem et al [12] investigated the behavior of RC slabs that had been exposed to fire. The fire duration was changeable and ranged from one to three hours in the first step (group A), while the concrete cover was fixed and equal to 25mm in the second step (group B). The concrete cover varied from 30 to 35 mm and 40 mm in the next step (group B), however the fire duration remained steady at 4 hours. The structure's responses are determined by the length of the fire and the thickness of the concrete cover. The RC (3100 mm × 3100 mm) slabs were modelled to show how varied slab thicknesses and fire durations affect the outcome. The two stages were also tested for deflection, lower strain, and upper strain of an RC slab at a temperature of 600 °C. The failure load decreases from 15.3 percent to 36.6 percent in the first stage (group A) when compared to the control slab. When compared to the control slab, the failure load in the second stage (group B) drops from 10.22% to 21.92%. And the failure load rises owing to a 22.2% increase in concrete cover thickness from 25 to 35 mm, which burned for the same amount of time (4 hours) at the same temperature.

Elwakkad et al. [37] studied the behavior of self-curing R.C. flat slabs. The Experimental program consists of two groups. The first group consist of five tested specimens have various reinforcement ratios (ρ) from 0.43% up to 1.08%. While the second group consist of central square openings with constant (ρ) of 0.57%. The results show that, using self-curing concrete (SCUC) by adding PEG-400 of 0.5 % reducing shrinkage, and early concrete desiccation. This was observed 28 days after self-curing the cast samples, in which no hair cracks were observed. Steel reinforcement ratio (ρ) has a substantial effect on improving crack load, and ultimate failure load of reinforced self-curing concrete flat slabs. The increase in (ρ) from 0.43 % up to 1.08 % increased the crack load by 12.5 % up to 25 %, respectively, while increasing the ultimate load by 18.2 % up to 72.7 %, respectively.

Based on the above, can be noticed that no previous studies have investigated the effect of fire at 600 °C on self-curing reinforced concrete flat slabs. In order to ascertain the impact of self-curing concrete on RC flat slabs exposed to fire, current research provides this experimental study. Main parameters of this study are reinforcement ratio (ρ), fire duration and cooling method.

To achieve these goals, twenty-five flat plates with dimensions (1200 × 1200 × 70) mm were cast and tested. The experimental program consists of five groups. Each group consist of five tested specimens having various steel reinforcement ratios (ρ) from 0.43% up to 1.08%. The tested specimens are exposed to high temperatures of (600°C). Slabs subjected to different exposure durations times of 1, and 2hours. The center deflections of field strip, cracking and failure loads were investigated in this term.

Due to the paramount importance of self-curing concrete, especially in the treatment of slabs, it is necessary to know its behavior under the influence of fire.

2. Experimental program

All tests were done in the Reinforced Concrete Laboratory, at the Faculty of Engineering, Menoufia University, Egypt. The experimental program consists of twenty-five specimens divided into five groups, as presented in Table 2. The first group represents the control specimens, which are not subjected to fire. The second and third groups represent specimens subjected to fire duration 1 and 2 hours, respectively and gradual cooling in air. While the fourth and fifth groups represent specimens subjected to fire duration 1 and 2 hours, respectively and sudden cooling using water. The main investigated variables are.

- Reinforcement ratio ρ: 0.43, 0.5, 0.72, 0.87, and 1.08%, were adopted.
- Duration of fire exposure: The specimens were subjected to direct flame for 1, and 2 h, respectively.
- Cooling technique: Two cooling techniques were used: rapid cooling with water sprayed directly over the hot surface of the slabs and gradual cooling in air.

Table 2: Details of the Test Specimens

Group	**Slab No.**	**Reinforcement Ratio (ρ) %**	**heat duration**	**Cooling Method**
I (Control Specimens)	SC1	0.43	-	-
	SC2	0.57	-	-
	SC3	0.72	-	-
	SC4	0.87	-	-
	SC5	1.08	-	-
II (Specimens Exposed to Fire 1H gradual cooling in air)	SFG11	0.43	1 Hour	Gradually
	SFG21	0.57		
	SFG31	0.72		
	SFG41	0.87		
	SFG51	1.08		
III (Specimens Exposed to Fire 2H gradual cooling in air)	SFG12	0.43	2 Hour	
	SFG22	0.57		
	SFG32	0.72		
	SFG42	0.87		
	SFG52	1.08		
IV (Specimens Exposed to Fire 1H sudden cooling using water)	SFSU11	0.43	1 Hour	Sudden
	SFSU21	0.57		
	SFSU31	0.72		
	SFSU41	0.87		
	SFSU51	1.08		
V (Specimens Exposed to Fire 2H sudden cooling using water)	SFSU12	0.43	2 Hour	
	SFSU22	0.57		
	SFSU32	0.72		
	SFSU42	0.87		
	SFSU52	1.08		

*S: Slab, C: Control Specimens, F: Fire, G: Gradually, SU: Sudden.

2.1. Test specimens

Twenty-five simply supported specimens with dimensions of (120×120×7cm) were cast for the current study. Each specimen has four corner-supports with dimensions of (l0×10×10 cm), with longitudinal reinforcement corner bars 4 Ø 10 mm. All specimens were produced from self-curing concrete using polyethylene glycol (PEG400) with an average compressive strength (F_{cu}) of 50

MPa after 28 days. The dimensions of the tested slabs, and their reinforcement details are shown in Figure (1).

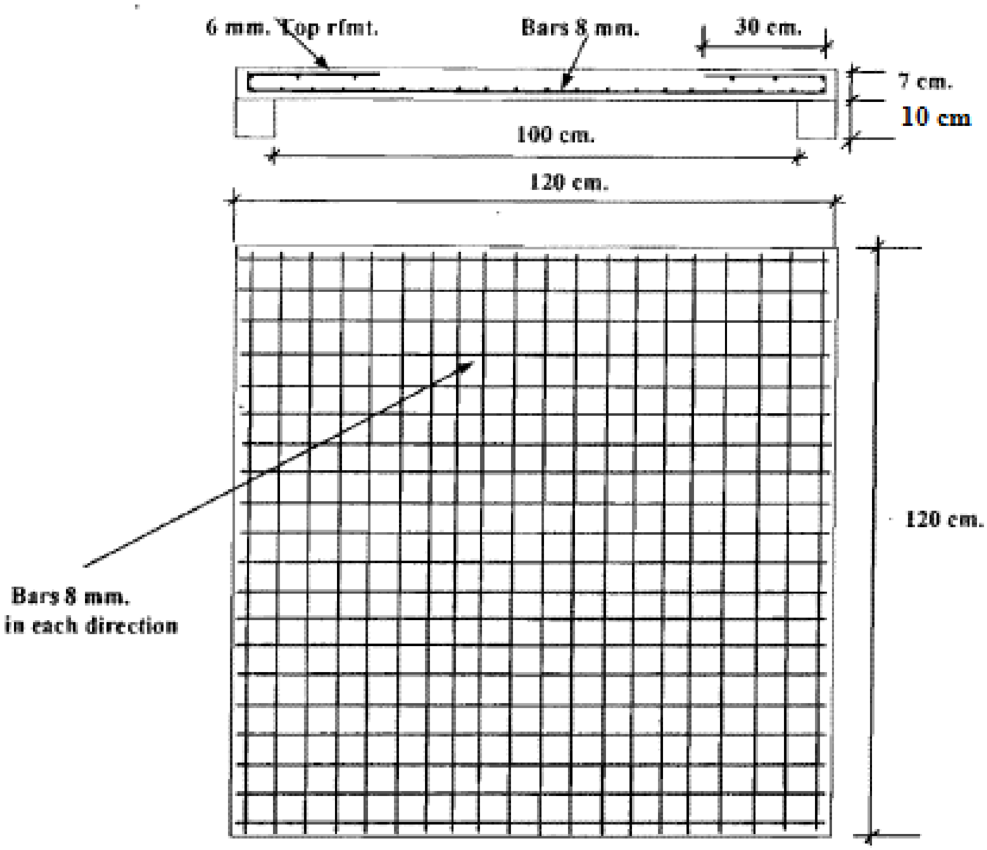


Fig. 1: Show dimensions and reinforcement details of the tested slabs

2.2. Material properties

In this study, Ordinary Portland Cement (OPC) CEM I 52.5 N, which is manufactured in Egypt. The properties of cement classified with E.S.S.373/91 demands [38] as shown in Table 3. Fly ash is a byproduct material of coal-fired power stations. In this study, fly ash is categorized as class F fly ash according to the requirement of ASTM C618 Class F [39]. The chemical composition and physical properties of fly ash is illustrated in Table 3. The fine aggregate used in this research is natural siliceous sand, clean and rounded fine aggregate with size 0.15mm–5 mm, a specific gravity of 2.6, and volume weight of 1.73 t/m^3. Coarse aggregates, which were used in this research, are local crushed dolomite, it was obtained from Attaka area, Egypt with a specific gravity of 2.64, a volume weight of 1.74 t/m^3, and with maximum size 13 mm. The physical properties of fine and coarse aggregates are shown in Table 4. A high-performance superplasticizer (SP) concrete admixture (Viscocrete-3425) was used to improve the workability of concrete mixtures. Viscocrete-3425 from SIKA Company [40] with a specific gravity of 1.08. The physical and chemical properties are listed in Table 5. The viscocrete-3425 dosage used was 2.1% from cement content 366 kg/m^3. In this study, Polyethylene Glycol (PEG-400) was used as a self-curing (SCU) agent in a liquid form, in order to prevent water evaporation from fresh concrete. The properties of Polyethylene Glycol-400 (PEG400) which manufactured by Morgan chemicals Pvt. Ltd in Egypt [41] are listed in Table (6). A PEG400 was used at ratios of 0.5% by the weight of cement. The plain bars (Ø 8mm) have been used as main reinforcement, with Yield stress of 240 MPa and elongation of 20%. The design of the mixture used is shown in Table 7. Table 8 shows the mechanical characteristics of the concrete mixture.

Table 3: Properties of Binder Materials.

Properties		Cement	Fly Ash
Physical properties	- Color	Grey	Light grey
	- Specific gravity	3.16	2.2
	- Specific surface area cm^2/gm	3380	8150
Chemical Composition (%)	- Silicon dioxide (Sio_2)	20.87	53.00
	- Aluminum oxide (Al_2o_3)	6.14	34.00
	- Ferric oxide (Fe_2o_3)	3.85	3.50
	- Sodium oxide (Na_2O)	*0.94*	0.72
	- Calcium oxide (Cao)	62.06	4.5
	- Magnesium oxide (Mgo)	2.48	1.50
	- Potassium oxide (K_2o)	0.78	0.60
	- Sulphur trioxide (So_3)	2.39	0.30

Table 4: Physical Properties of Dolomite and Sand.

Description	Dolomite	Sand
Volume Weight	1.74 t/m^3	1.73 t/m^3
Specific Gravity	2.64	2.6
% Absorption	0.76	0.78
Void Ratio	34.34 %	33.81 %

Table 5: The Chemical and Physical Properties of Viscosity Enhancing Agent (VEA) Admixture [40]

Property	Data
Type	Aqueous solution of modified polycarboxylates
Appearance	Clear liquid
Density	1.08 Kg/lt. ± 0.005
PH Value	4.0
Solid content	40% by weight
Storage	Protected from direct sun light and frost at temperature between +5 ^oC and +35 ^oC
Shelf life	12 months from date of production

Table 6: Characteristic of Polyethylene Glycol 400 [41].

Type	Molecular Weight	Hydroxyl Num ber, Mg KOH/g	20 °C	Liquid Density, g/cc 60 °C	80 °C	Freezing Range, °C	Solubility in Water at 20 °C, % by wt	Viscosity 100°C
PEG 400	380 to 420	264 to 300	1.1255	1.0931	1.0769	4 to 8	complete	7.3

Table 7: Concrete mix.

Mix proportions (Kg / m^3)						
Cement [38]	Crushed dolomite	Sand	Fly Ash [39]	Viscocrete-3425 [40]	Water	PEG400% [41]
366	1128	817	19	7.7	140	0.5

Table 8: Mechanical characteristics of concrete mixture.

Strength	Days		
	7	14	28
Compression (MPa)	42.4	47.5	50
Tensile (MPa)	3.6	4.9	5.1

3. Preparation of specimens

First, aggregate (crushed dolomite and sand) was mechanically blended for one minute. Second, cement and fly ash were mixed into the dry mixture for about two minutes. The third step is to mix water, polyethylene glycol 400 and a superplasticizer together. Fourth, the dry mixture was combined for 3 minutes with 60% liquids (Sika-Viscocrete 3425, PEG 400, and water). Finally, residual liquids were used to stir the mixture for 5 minutes. After casting, the specimens have been cured as self-curing in the laboratory atmosphere for 28 days, and then they have been exposed to fire at temperature 600 °C, then the samples have been loaded till failure.

3.1. Fire application to specimens

Fire flame by burners was used for heating the RC slab specimens at 600 °C temperature at their tension face. A digital temperature controller has been used to monitor the temperature continuously. To measure the temperature, the thermocouple was placed at contact with the flame with the sample surface, as illustrated in Figure (2). Specimens were kept at the target temperature for 1 hour and 2 hours, respectively.

Fig. 2. Expose the sample to fire.

3.2. Test setup and instrumentation

Four corner supports were used to support the RC plates. Each support was made of (l0 × 10 × 10 cm) reinforced concrete with four mild steel longitudinal corner bars (4 Ø10). As shown in Fig. (3), a hydraulic jack with load capacity of 100 kN was used as one concentrated load at the center of the plate. Each specimen has been loaded up to failure. To record vertical deflections, three vertical dial gauges of total capacity of 25 mm and 0.01 mm accuracy were used.

Fig. 3. Test setup

4. Experimental results and discussion

4.1. Pre-loading fire effect

Some hair cracks appeared on the heated tension side after specimens were exposed to fire. The diameter of those fissures widened as the blaze exposure time increased. Water-cooled slabs had wider cracks than those that were gradually cooled.

4.2. Influence of steel reinforcement ratios (ρ)

Five ratios of ρ (0.43, 0.57, 0.72, 0.87, and 1.08%) were used in Group I as control set to examine the effect of (ρ) on the flexural behavior of self-curing reinforced concrete flat slabs. The findings of this parameter are shown in Table (9), and it was found that the steel reinforcement ratios significantly affect the cracking, ultimate loads, and maximum deflection. The first crack load increased by 5.88%, 5.88%, 11.76%, and 17.64% with the rise of (ρ) from 0.43 to 0.57, 0.72, 0.87, and 1.08, respectively as a percentage. While the ultimate load likewise increased as the ratios of steel reinforcement increased, by 18.20%, 45.4%, 54.50%, and 72.70%, respectively. Due to enhanced steel reinforcing and better crack management, increasing the initial cracking load reduced of flexural micro-cracks expanding further. At an ultimate load of 22 kN, slab SC1 experienced the most deflection, measuring 9.11 mm. In contrast, slabs SC2, SC3, SC4, and SC5 experienced deflection values of 4.30, 2.80, 2.00, and 1.72 mm, respectively. The effect of (ρ) on load-deflection curves is shown in Figure (6), which emphasizes how the deflections decreased as (ρ) increased during all stages of loading. As a result of this, the relationship between the deflection value and the (ρ) steel reinforcement ratio was inverse. As for the Group II, that exposed to elevated temperature 600 °C for one hour, and which has been gradually cooled the cracking load decreased comparing by the control set by 29.4 %, 22.2%, 22.2%, 15.8% and 20% for the specimens SFG11, SFG21, SFG31, SFG41, and SFG51 respectively. While the ultimate failure load decreased by 9.1%, 11.5%, 6.3%, 8.8% and 10.5%, respectively. And the deflection record increased up to 3.8%. For group III, it has been noticed decreasing in cracking and ultimate load up to 60%, and 27.3% respectively. While the values of deflection increased up to 9.4%. The reduction in cracking and ultimate loads values and increase in deflection values are due to an increase in fire exposure duration to which the samples were exposed to two hours. But in Group IV, that exposed to elevated temperature 600◦c for one hour, and which has been sudden cooled the values of decreasing cracking and failure loads reached to 41.2%, 21.1% respectively, and deflection increased up to 8.6%. Finally, in Group V, which were exposed to 2h fire was cooled with water which was applied directly to the heated face of the specimens, the values of decreasing cracking and failure loads reached 70%, 40.9% respectively. And the deflection increased up to 13%. These findings are consistent with those by Elwakkad et al. 2022; Heizer et al. 2005; Vui et al. 2022; François et al. 2022; Ola et al. 2018; Mortada, 2015; Qasim et al. 2018 [37,42-46], and with previous studies on the physical and mechanical properties of SCUC (self-curing concrete), such as Elwakkad and Heizer 2019; Bashandy 2015; Sideris and Manita [47-49].

Table 9: Test Results

Group	Slab No.	Cracking Load (kN)	Reduction (%)	Ultimate Load (kN)	Reduction (%)	Max. Deflection (mm)	Increase (%)
I	SC1	17	-	22	-	9.11	-
	SC2	18	-	26	-	9.34	-
	SC3	18	-	32	-	11.78	-
	SC4	19	-	34	-	10.2	-
	SC5	20	-	36	-	9.21	-
II	SFG11	12	29.4	20	9.1	9.45	3.7
	SFG21	14	22.2	23	11.5	9.67	3.5
	SFG31	14	22.2	30	6.3	11.96	1.5
	SFG41	16	15.8	31	8.8	10.4	2.0
	SFG51	16	20.0	34	10.5	9.56	3.8
III	SFG12	8	52.9	16	27.3	9.97	9.4
	SFG22	10	44.4	20	23.1	10.05	7.6
	SFG32	10	44.4	24	25.0	12.46	5.8
	SFG42	12	36.8	26	23.5	10.85	6.4
	SFG52	8	60.0	28	26.3	10.05	9.1
IV	SFSU11	10	41.2	18	18.2	9.89	8.6
	SFSU21	12	33.3	21	19.2	9.91	6.1
	SFSU31	12	33.3	26	18.8	12.24	3.9
	SFSU41	14	26.3	28	17.6	10.66	4.5
	SFSU51	12	40.0	30	21.1	9.88	7.3
V	SFSU12	6	64.7	13	40.9	10.23	12.3
	SFSU22	8	55.6	17	34.6	10.19	9.1
	SFSU32	8	55.6	20	37.5	12.75	8.2
	SFSU42	8	57.9	21	38.2	10.94	7.3
	SFSU52	6	70.0	26	31.6	10.41	13.0

4.3. Load-deflection relationships

Using dial gauges with an accuracy of 0.01 mm and a diameter of 10 mm, the load deflection curves were recorded. Three sites positioned along the middle line of the RC plates were used to record the deflection values for each specimen. The deflections of the control slabs reinforced with various (ρ) are shown in Figure (4). The load deflection relationship for several slabs that has the same (ρ) is shown in Figures (5-9).

The deflection proportion and reinforcement ratio are oppositely correlated. The maximum deflection was recorded by slab SC1, which has the lowest reinforcement ratio, and the minimum deflection was recorded by slab SC5, which has the highest reinforcement ratio. While the load-deflection relationships for the rest tested RC slabs, the ultimate deflection increases as the fire period increases. This is due to fire damage to the specimens, which reduces the stiffness of the plates and so increases their deformability.

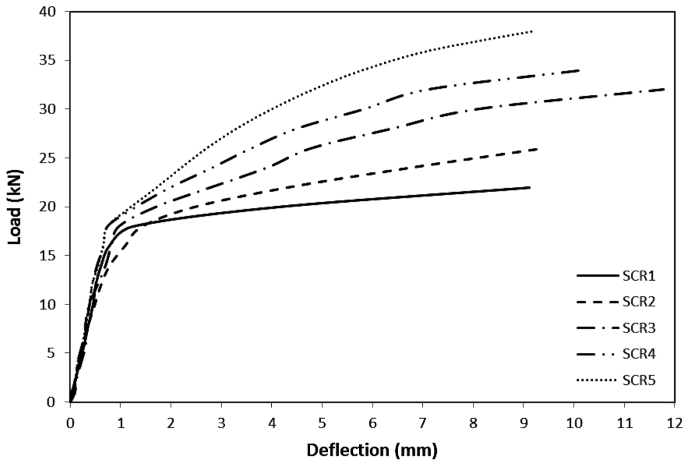


Fig. 4. Load -deflection curves of group (I)

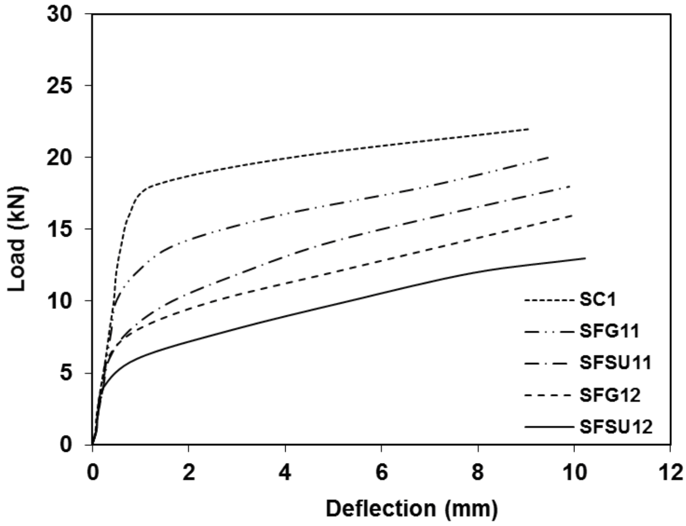


Fig. 5. Load-deflection curves for specimens with reinforcement ratio 0.43%

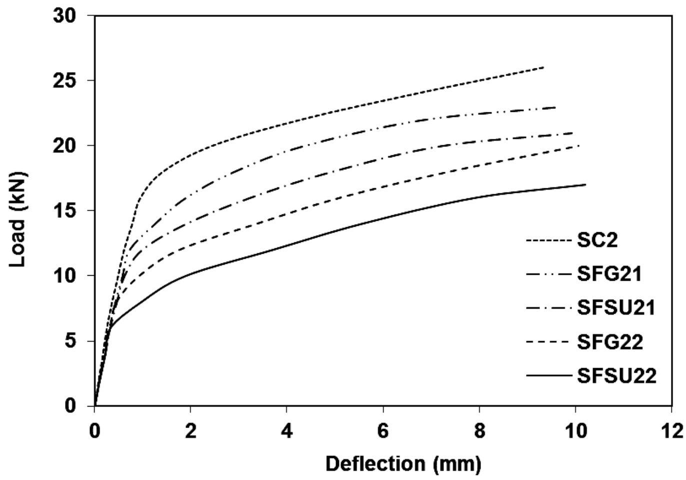


Fig. 6. Load-deflection curves for specimens with reinforcement ratio 0.57%

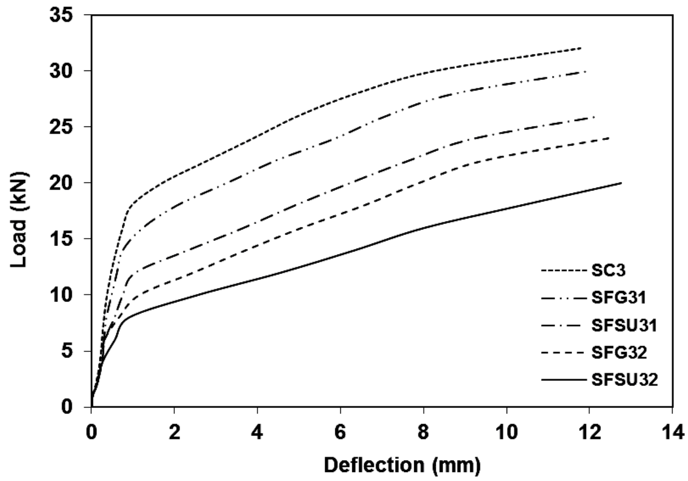


Fig. 7. Load-deflection curves for specimens with reinforcement ratio 0.72%

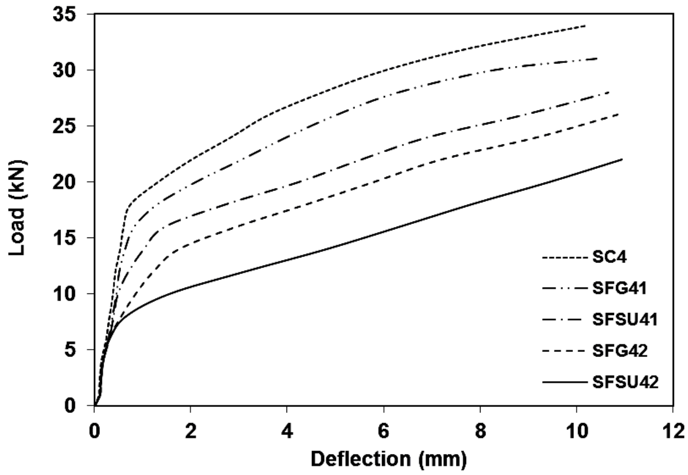


Fig. 8. Load-deflection curves for specimens with reinforcement ratio 0.87%

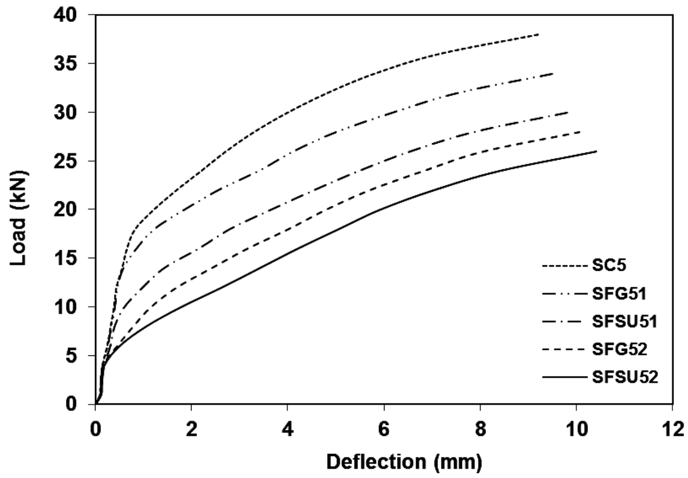


Fig. 9. Load-deflection curves for specimens with reinforcement ratio 1.08%

4.4. Pattern of cracking and mode of failure

The failure of all specimens under pure bending is generally depicted in figures (10-11).
According to test results, all slabs under loading exhibited the following general behavior: Flexural cracks started in the slab tension side near the center of all specimens and progressed diagonally to the slab borders, as seen in Figs. (10-11) by increasing load.
The number of cracks and their widths increased as the load raised. No spalling on the surfaces of slab occurred, a complete failure occurred, and all of the tested slabs failed in flexure.

Fig. 10. Crack pattern of SFG11

Fig. 11. Crack pattern of SFG21

4.5. Effect of elevated temperature

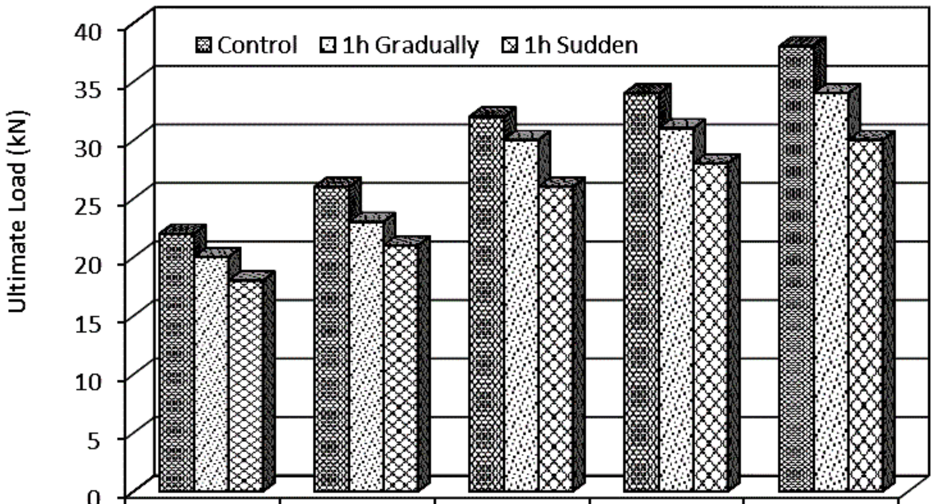
Table (9) shows a lowering in cracking loads, and a lowering in failure loads were all listed as a result of the influence of high temperature on slabs. The effect of high temperature (600 °C) on first cracking load shown as a percentage decreasing in cracking load when compared with control specimens, with a maximum lowering of 70%. The influence of temperature on ultimate load is shown as a percentage lowering in ultimate load when compared to control specimens, with a maximum decreasing of 40.9%. These findings agree with the study [50].

4.6. Effect of fire duration

When samples were exposed to fire for longer periods of time, it was noticed that the deflection values for specimens rose significantly. As shown in the table (9) the values of the cracking and ultimate loads reduction up to 50% and 20%, respectively for 2h exposure compared to 1h exposure.

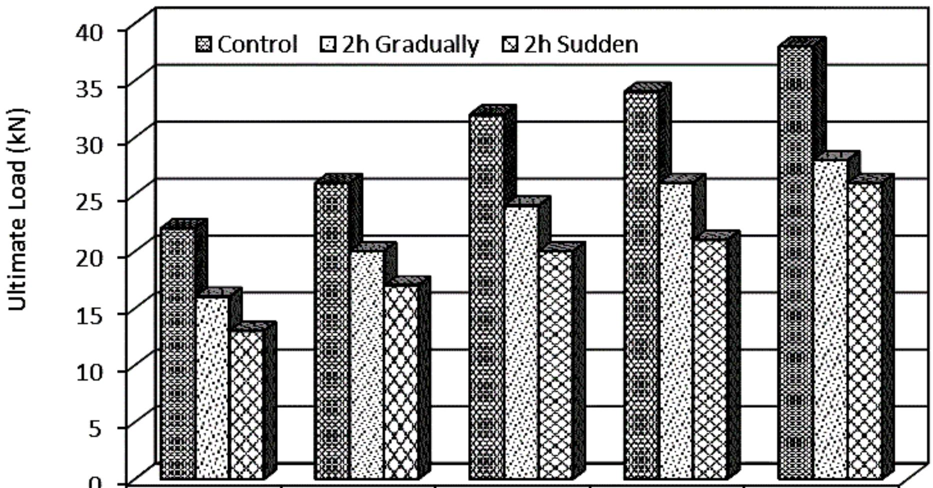
4.7. Effect of cooling method

As shown in Figs. 12 and 13, the gradually cooled specimens have been noticed reduction values from 15.8% to 60% of cracking load. On the other hand, the specimens which have been suddenly cooled the cracking load reduction values range from 26.3%-70%. As for the ultimate load, the reduction values have ranged from 6.3% to 26.3% in the case of gradual cooling. But in the case of sudden cooling, the reduction values have ranged from 17.6% to 40.9%. On the other hand, it's clear from Fig. 12 that the specimens which have been suddenly cooled had a 15% lower ultimate capacity than the gradually cooled specimens. The drop in ultimate strength caused by abrupt cooling is explained by concrete shrinkage, which causes new fractures, resulting in significant strength loss. However, the deflection values increased by about 9.1%, and 13% in case of gradually and sudden cooling respectively.



	SC1	SC2	SC3	SC4	SC5
Control	22	26	32	34	38
1h Gradually	20	23	30	31	34
1h Sudden	18	21	26	28	30

Fig. 12. Cooling method effect on ultimate load for 1h



	SC1	SC2	SC3	SC4	SC5
Control	22	26	32	34	38
2h Gradually	16	20	24	26	28
2h Sudden	13	17	20	21	26

Fig. 13. Cooling method effect on ultimate load for 2h

5. Conclusions

The effect of fire at 600 °C on self-curing RC flat slabs heated at their tension side is investigated in experimental research. The results could lead to the following conclusions.

1. When slabs were exposed to fire, random hair cracks appeared at the face subjected to heat, which reduced the cracking load and failure load by up to 70% and 40.9%, respectively.
2. Steel reinforcement ratio (ρ) has a substantial effect on improving crack load, and ultimate failure load of reinforced self-curing concrete flat slabs. The increase in steel reinforcement ratio (ρ) from 0.43 % to 0.57%, 0.72%, 0.87%, and 1.08% increased the crack load by 5.88%, 5.88%, 11.76%, and 17.64%, respectively, while increasing the ultimate load by 18.20%, 45.4%, 54.50%, and 72.70%, respectively. However, the maximum deflection values were not proportional to the increasing steel reinforcement ratio (ρ).
3. Concrete loses stiffness when exposed to fire, which significantly increases its deformability.
4. Longer fire exposure caused concrete to deteriorate and specimen temperatures to significantly rise. In comparison to one hour of exposure, a final load reduction of up to 20% was noted during two hours of exposure.
5. The ultimate loads were found to be 15% lower with sudden cooling compared with progressive cooling. This is explained by the concrete suddenly shrinking, which results in new cracks and a significant loss of strength.

References

[1] A. H. Gustaferro, CRSI. Engineering Practice Committee & CRSI. Committee on Fire Ratings, Reinforced concrete fire resistance, 1st edn, Concrete Reinforcing Steel Institute, Chicago, 1980.

[2] T. Z. Harmathy, Fire safety design and concrete, Longman Scientific & Technical; Wiley, Harlow, Essex, England, New York, NY, 1993.

[3] J. A. Purkiss, Fire safety engineering design of structures, Butterworth-Heinemann, Oxford; Boston, 1996.

[4] A. H. Buchanan, Structural design for fire safety, Wiley, Chichester, England, New York, 2001.

[5] C. Fleischmann, and A. H. Buchanan, “Analytical methods for determining fire resistance of concrete members, in The SFPE Handbook of Fire Protection Engineering,” Third Edition, ed. DiNenno, P. J., National Fire Protection Association, Massachusetts, pp. 4-256, 2002.

[6] C. A. Wade, 'Fire engineering design of reinforced and prestressed concrete elements', in BRANZ Study Report, Building Research Association of New Zealand, no. 33, 1991.

[7] S. EL-Fitiany, and M. Youssef, “Interaction Diagrams for Fire-Exposed Reinforced Concrete Sections, Canadá, Engineering Estructures,” vol. 70, pp. 246-259, 2014.

[8] G. A. Khoury, “Effect of Fire on Concrete and Concrete Structures,” Progress in Structural Engineering and Materials, vol. 2, no. 4, pp. 429-447, 2000.

[9] L. F. Caetano, Estudo do comportamento da aderência em elementos de concreto armado submetidos à corrosão e elevadas temperaturas, Porto Alegre, Dissertação (Mestrado em Engenharia) - Programa de Pósgraduação em Engenharia Civil, Universidade Federal do Rio Grande do Sul, 153 f, 2008.

[10] M. M. Karim, “Investigation of the Behavior and Properties of Reinforced Concrete Slabs Exposed to Fire Flame,” Master Thesis, Babylon University, Babylon, Iraq, 2005.

[11] P. S. R. Prasad, “Effect of Fire on RC Slab,” International Journal for Innovative Research in Science & Technology, vol. 3, Issue 04, 2016.

[12] G. Ghanem et al., “Behavior of Reinforced Concrete Flat Slab Exposed to Fire Experimentally and Numerically by (ANSYS)”, Journal of Mechanical and Civil Engineering, vol. 13, Issue. 6, pp. 25-42, 2016.

[13] S. M. Allam, H. M.F. Elbakry, and A. G. Rabeai, “Behavior of one-way reinforced concrete slabs subjected to fire,” Alexandria Engineering Journal, vol. 52, pp. 749-761, 2013.

[14] R. Kh. S. Al-Hamd, M. Gillie, S. A. Mohamad, and L. S. Cunningham, “Influence of loading ratio on flat slab connections at elevated temperature: A numerical study,” Frontiers of Structural and Civil Engineering, vol. 14, pp. 664–674, 2020.

[15] H. Sadaghian, and M. Farzam, “Numerical investigation on punching shear of RC slabs exposed to fire,” Computers and Concrete, vol. 23, no. 3, pp. 217-233, 2019.
[16] W. A. Waryosh, and H. H. Hashim, “Behavior of reinforced concrete bubbled slabs exposed to fire flame under static load,” International Journal of Latest Engineering Research and Applications (IJLERA), vol. 4, no. 12, pp. 25-37, 2019.
[17] A. A. Abdul-Razzak, and A. H. Said, “Nonlinear analysis of reinforced concrete slabs at elevated temperature,” Iraqi Journal of Civil Engineering, vol. 9, pp. 42-51, 2010.
[18] P. J. Moss, R. P. Dhakal, G. Wang, and A. H. Buchanan, “The behaviour of multi-bay two-way reinforced concrete slabs in fire,” Engineering Structures, vol. 30, no. 12, pp. 3566-3573, 2008.
[19] H. Salem, H. Issa, H. Gheith, and A. Farahat, “Punching shear strength of reinforced concrete flat slabs subjected to fire on their tension sides,” Housing and Building National Research Center HBRC Journal, vol. 8, pp. 36-46, 2012.
[20] C. Sangluaia, M. K. Haridharan, C. Natarajan, and A. Rajaraman, “Behaviour of reinforced concrete slab subjected to fire,” International Journal of Computational Engineering Research, vol. 3, no. 1, pp. 195-206, 2013.
[21] Z. Huang, I. W. Burgess, and R. J. Plank, “Nonlinear Analysis of Reinforced Concrete Slabs Subjected to Fire,” Structural Journal, vol. 96, no. 1, pp. 127-135, 1999.
[22] G. Ghanem, T. Ali, M. Nooman, and M. Kadry, “Behavior of reinforced concrete flat slab exposed to fire experimentally and numerically by (ANSYS) ,” IOSR Journal of Mechanical and Civil Engineering, vol. 13, no. 6, pp. 25-42, 2016.
[23] L. Lim, A. Buchanan, P. Moss, and J. M. Franssen, “Numerical modelling of two-way reinforced concrete slabs in fire,” Engineering Structures, vol. 26, no. 8, pp. 1081-1091, 2004.
[24] G. Wang, “Performance of reinforced concrete flat slabs exposed to fire,” Master thesis, University of Canterbury, Christchurch New Zealand, 2006.
[25] S. Poorna, and R. Prasad, “Effect of fire on RC slab,” International Journal for Innovative Research in Science & Technology, vol. 3, no. 4, pp. 179-183, 2016.
[26] A. Balaji, “Praveen Nagarajan, T.M. Madhavan Pillai, Predicting the response of reinforced concrete slab exposed to fire and validation with IS456 (2000) and Eurocode 2 (2004) provisions,” Alexandria Engineering Journal, vol. 55, no. 3, pp. 2699-2707, 2016.
[27] S. J. George, and Y. Tian, “Structural performance of reinforced concrete flat plate buildings subjected to fire,” International Journal of Concrete Structures and Materials, vol. 6, no. 2, pp. 111–121, 2012.
[28] I. A. Fletcher, S. Welch, J. L. Torero, and R. O. Carvel, “Asif Usmani, The Behaviour of Concrete Structures in Fire,” Thermal Science, vol. 11, no. 2, pp. 37-52, 2007.
[29] A. M. Hassan, “Behavior of Continuous Flat Slab Exposed to Fire,” World Applied Sciences Journal, vol. 23, no. 6, pp. 788-794, 2013.
[30] Kh. A. Abouleiwun, H. M. F. Elbakry, M. A. Diab and S. F. El-Fitiany, “Behavior of RC flat plate structure subjected to compartment fires,” Journal of Structural Fire Engineering, 2022.
[31] J. Ožbolt, D. Ruta, and B. Irhan, “Numerical study of reinforced concrete slabs under extreme loading conditions: Impact and fire,” IOP Conf. Series: Materials Science and Engineering, vol. 615, 2019.
[32] M. M. A. Filho, P. A. G. Piloto, and C. Balsa, “The load-bearing of composite slabs with steel deck under natural fires,”, AIMS Materials Science, vol. 9, no. 1, pp. 150-171, 2022.
[33] L. Choe, S. Ramesh, C. Zhang, and C. Clifton, “Behavior of Composite Floor Assemblies Subject to Fire,” Influence of Slab Reinforcement, vol. 4, 2021.
[34] A. H. Gharbi, and A. S. Mahmoud, “Punching Shear Behavior of Reinforced Concrete Slabs under Fire using Finite Elements,” Journal of Engineering, vol. 26, 2020.
[35] D. M. Manley, “Design of Reinforced Concrete Slabs Exposed to Natural Fires,” University of Canterbury Fire Engineering Conference, Christchurch, New Zealand, April 29, 2014.
[36] A. A. Zende, A. V. Kulkarni, and A. Hutagi, “Behavior of Reinforced Concrete Subjected to High Temperatures-A Review,” Journal of Structural Fire Engineering, vol. 4, 2013.
[37] N. Y. Elwakkad, B. A. Tayeh, Gh. M. Hekal, and Kh. M. Heiza, “Experimental and numerical investigation of the behavior of self-curing R.C. flat slabs,” Case Studies in Construction Materials, vol. 17, 2022, https://doi.org/10.1016/j.cscm.2022.e01457

[38] ECCS 373/1991 Specification for Ordinary Portland Cement Egyptian Standards
[39] Sika fly ash concrete additive, https://egy.sika.com/content/dam/dms/eg01/e/Sika%20Fly%20Ash.pdf
[40] Sika-Viscocrete 3425, Sika Egypt for Construction Chemicals S. A. E. International.
[41] Morgan Chemical Pvt. Ltd Industries Co. in Egypt. https://www.findinegypt.com/c/morgan-chemical-industries-co-263265.
[42] Kh. M. Heiza, N. Farah, N. N. Melaka, and M. A. Tayel, "Experimental study of high strength concrete slabs," ERJ Journal, vol. 28, no. 1, 2005.
[43] V. V. Cao, H. B. Vo, L. H. Dinh, and D. V. Doan, "Experimental behavior of fire-exposed reinforced concrete slabs without and with FRP retrofitting," Journal of Building Engineering, Elsevier 51, 2022, https://doi.org/10.1016/j.jobe.2022.104315
[44] F. P. d'Entremont, and G. J. Poitras, "Bending strength of composite slabs exposed to fire at an early age," Fire Technology, vol. 58, pp. 3509-3527, 2022.
[45] M. A. Ismael, "Flexural behavior of steel fiber-self compact concrete slabs," Diyala Journal of Engineering Sciences, Second Engineering Scientific Conference, College of Engineering-University of Diyala, ISSN 1999-8716, pp. 83-99, 2015.
[46] O. A. Qasim, and R. Abdulsattar, "Experimental and analytical study of behavior of ultra high self compacted hollow core reinforced concrete one-way slabs," International Journal of Applied Engineering Research, vol. 13, no. 2, 2018, 1035-1055, ISSN 0973-4562.
[47] N. Y. Elwakkad, and Kh. M. Heiza, Mechanical properties of self-curing concrete (SCUC), Challenge Journal of Concrete Research Letters, vol. 1, 2019, ISSN: 2548-0928 /DOI: https://doi.org/10.20528/cjcrl.2019.01.001
[48] A. A. Bashandy, "Performance of self-curing concrete at elevated temperatures," Indian Journal of Engineering & Material Sciences, vol. 22, pp. 93-104, 2015.
[49] K. K. Sideris, and P. Manita, "Residual mechanical characteristics and spalling resistance of fiber reinforced self-compacting concretes exposed to elevated temperatures," Construction and Building Materials, vol. 41, pp. 296-302, 2013.
[50] V. Afkhami, E. Dehghani, and M. Arezoumandi, "Effect of exposure to fire on a concrete slab with calcareous aggregate," Asian Journal of Civil Engineering, 2021. https://doi.org/10.1007/s42107-021-00366-z