Damage assessment of RC voided slabs experienced extreme fire flame

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Abstract. The main objective of this study was to assess the damage level in reinforced concrete voided slabs experimentally after exposure to high fire flame. Accordingly, four analogous slabs were created using the same concrete strength with dimensions of 500 mm long x 270 mm wide x 90 mm deep. They contained fifteen plastic balls with a 70 mm diameter, placed in between the top and bottom reinforcement meshes. Three specimens were subjected to direct fire flame using a diesel furnace at 200 ºC, 500 ºC, and 800 ºC for one hour. The fourth was left without burning for the contrast purpose. Afterward, the slabs were tested under uniformly distributed loads up to collapse. The results indicated that the slabs' failure mode changed from combined flexural-shear to pure shear when the temperatures passed 200 ºC. The residual strengths of 200-800 ºC exposed slabs downed to 71.80%-52.00% relative to the unexposed one, respectively. As well, the ductility, service stiffness, and toughness of burned slabs remarkably decreased, approaching 65.97%, 54.18%, and 77.82%, respectively.

1. Introduction

Voided slabs are a construction system proposed by Jorgen Breuning, a Danish engineer, in 1990 to lighten the self-weight of slabs considerably, up to 35%. In such slabs, plastic voids with various shapes are placed between the top and bottom reinforcement meshes, and therefore, a significant size of concrete is removed [1]. Accordingly, this type of slabs earns several gains, including material-saving, a positive effect on the environment due to reducing pollutants associated with the cement manufacturing process, large space buildings, and no need for huge supporting members like columns and foundations. Also, this type has sufficient strength with relatively small deformations [2].

After 1990, many studies were conducted on such slabs [3–6]. Firstly, the authors directed their attention to the flexural strength of voided slabs. They discovered that the voided slabs could reach the same flexural strength as solid ones for the same depth. Nevertheless, a considerable decline in the shear strength of voided slabs was reported, around 27-40% lower than the conventional slabs.

The next study performed by Chung et al. [7] focused on the influence of material and shape of used voids; the results demonstrated that only the shear strength of slabs was observed to be influenced by the voids’ materials, while the formers’ shape impacted both the shear strength and crack configuration prominently.

Then, the researchers’ have concentrated their consideration on the punching strength of voided slabs. These investigations [8,9] addressed significant decays in the punching strength of slabs as a consequence of placing voids within the critical zone, responsible for withstanding the punching force, near the supporting columns. In this region, the removed concrete has a substantial contribution to the punching capacity of slabs. The posterior research recommended introducing a solid area, without voids, around the columns’ edges to overcome this problem. Thereby, different shapes for the solid area were
suggested ranged from simple to tedious [10]. Based on the results of Schnellenbach-Held et al. [11], shifting the voids by d/2 (where d is the effective depth of slabs) from the column face was suitable in gaining the same punching strength as the solid slabs. However, other studies [12,13] showed opposing observations, where notable declines in the punching strength, approaching 35-50%, were recorded even though the voids were placed at a distance of 1.5 times the slab depth apart from the column edge.

One of the severe challenges that reinforced concrete (RC) buildings may face is exposure to fire accidents, and therefore, all elements of facilities should have sufficient fire resistance to avoid the catastrophic collapse, especially slabs that have a broad area, compared to other components, to be exposed to fire. In general, concrete has features that make it accurate resistent to high temperatures, including minor thermal conductivity and excellent thermal ability [14,15]. Despite these characteristics, a remarkable variation in concrete mechanical properties was listed due to hard microstructural modification associated with high fire flames [16]. In RC members, the fire impairment level was found to be interrelated to parameters, such as the properties of principal materials, restriction degree, and the fire scenario [17].

In the previous, many attempts have been introduced to understand the influence of fire flame on RC elements. Regarding slabs, the former investigations [18,19] explained the ability of heat to transmit along all sides of slabs due to their semi-infinite dimensions. However, the two-way supported slabs were found to be more excellent in resisting the fire flame than the one-way rested slabs because of membrane action [20]. Also, the response of hollow-core slabs in the fire was further complex than that of solid ones. This finding was attributable to discontinuity in transforming heat through hollows existing at the center of slabs [21]. For bubbled slabs, Waryosh and Hashim [22] carried out an experimental program on seven slabs. Some of them were burned to 400 ºC; this investigation concentrated on repairing the fire-damaged slabs using CFRP. The results stated that the concrete spalling was observed when the fire temperature passed 300 ºC, and the peak strengths of retrofitted slabs were 88-105% of the strength of the unexposed slab.

The need for further investigations on voided slabs exposed to high fire flame is clear from the previous review. Accordingly, an experimental scheme was performed in this study, where four voided slabs were created. Three specimens were exposed to different temperatures, reaching 800 ºC, and then tested under uniformly distributed loads. The discussion of results was expanded to include the fire impacts on ductility, stiffness, and toughness of slabs in addition to their residual strengths.

2. Test Specimens
The experimental work program consisted of 4 bubble slabs. They were fabricated in matching details; their dimensions were 500 mm long, 270 mm wide, and 90 mm thick. These relatively small dimensions are chosen to fit the furnace size, which was used to burn the samples. Regarding the reinforcement, the slabs were reinforced at the top and bottom. Both meshes consisted of 6-Ø4 mm in the main direction and 10-Ø4 mm in the transverse direction. The yield strength of employed bars was 508 MPa. For each sample, fifteen plastic balls were inserted in between the reinforcement meshes arranged in a form, allowing them to comprehend voids in their prearranged position, as demonstrated in Figures 1 and 2. The plastic balls have been frequently used in voided slabs [23,24]. The diameter of these balls was 70 mm. The ratio of bubbles’ diameter/slab depth was 0.77; this ratio agreed with the design guide of bubble decks [25]. The voided slabs lost about 47% of their weight due to inserting these balls. After placing the reinforcement cages into molds, the specimens were cast using the same concrete mix and batch. The mix proportion was 1 (cement, 360 kg/m³): 1.77 (sand, 637 kg/m³): 2.22 (gravel, 799 kg/m³) in weight with a water to cement ratio of 0.55. The selected cement was ordinary Portland cement, while the gravel was crushed, washed, and well-graded with an 8 mm peak size. The used materials specified the Iraqi specifications for cement and aggregates [26,27]. The adopted mix gained a compressive strength of 24.8 MPa at 28 days based on the mean of eight 150 mm-standard cubes. Beyond casting, the slabs and supplementary cubes were cured in the moist condition at a room temperature of 25 ºC for 28 days. After that, the specimens were equipped for the burning and then testing processes.
A diesel furnace with a size of 1100 x 770 x 450 mm, shown in figure 3, was utilized for the burning purpose. This furnace has the ability to expose fire flame from all sides with different degrees and durations through a digital monitor that can be computerized easily. Herein, three specimens were burned separately at temperatures of 200 °C, 500 °C, and 800 °C for one hour, whereas the fourth was the control slab that was left unburned. Therefore, the specimens were recognized by terms, comprising two letters BS, which are the first letters of Bubbled Slabs, followed by numbers, referencing the fire temperatures, as listed in table 1. Once the planned fire scenario had been attained, the burned specimens were gradually cooled down by leaving them inside the turned-off furnace. Then, they were taken out and prepared for testing. It is substance stating that surfaces of fire-exposed slabs were reviewed accurately, and random hair cracks were observed to spread on these faces; these cracks were more apparent and huge for slabs undergone the higher fire flame temperature.

3. Test Setup

The specimens were subjected to uniformly distributed loads after the fire exposure had been finished. The slabs were positioned inside the testing frame and rested simply with a clear span of 450 mm, as illustrated in figure 4. The mechanism of applying the uniform loads is explained in figure 5; the concentrated loads were applied to a loading steel plate through a hydraulic jack located at the lower part of the testing machine. This loading plate transferred the applied loads to the sandbag on which the compression face of slabs was placed. Hence, a cogent uniformly distributed loads could be realized. The loadings were subjected regularly till failure, and the vertical displacement at the center of slabs was read using a dial gauge of 0.01 mm accuracy at each load augmentation.

| Slab designation | Thickness (mm) | Temperature (°C) | Exposure time (hour) | Method of cooling |
|------------------|----------------|------------------|----------------------|------------------|
| BS-25            | 90             | 25               | -                    | -                |
| BS-200           | 90             | 200              | 1                    | gradual          |
| BS-500           | 90             | 500              | 1                    | gradual          |
| BS-800           | 90             | 800              | 1                    | gradual          |

**Figure 1.** Details of tested specimen. **Figure 2.** Locations of steel reinforcement and the plastic balls.
4. Test Results

4.1. cracking patterns and failure modes

A combined flexural-shear failure was observed only in two specimens, which were the control (BS-25) and the burned at 200 °C (BS-200). In these slabs, the first flexural cracks were initiated at the mid-span, the peak moment zone. After that, with the extra load, more cracks formed and distributed over the middle third of the slab's span, while the former cracks expanded and propagated deeper, headed for the compression face of slabs. The failure happened when diagonal cracks appeared near the supports; these cracks developed and traveled towards the compression slabs faces quickly, as shown in figure 6.

The failure mode changed entirely to the pure shear mode for slabs burned at a temperature higher than 200 °C (BS-500 and BS-800), as presented in Figure 6. The flexural cracks were few in this mode and did not advance above the slabs' neutral axis, whereas significant inclined shear cracks occurred close to support. The collapse took place once the inclined shear cracks had reached the compression surface of slabs. The alteration in the failure mode can be imputed to the enormous drop in the concrete strength when exposed to a fire flame greater than 300 °C [28,29]. Therefore, the shear capacity of slabs remarkably declined since it depends mainly on the concrete grade [30,31], and hence, the shear mode was governing in slabs BS-500 and BS-800.
Figure 6. Failure cracks pattern for (a) BS-25, (b) BS-200, (c) BS-500 and (d) BS-800.

Table 2. Results of tested specimens.

| Specimens | Ultimate load (kN) | Residual strength (%) |
|-----------|--------------------|-----------------------|
| BS-25     | 50.00              | 100.00                |
| BS-200    | 35.90              | 71.80                 |
| BS-500    | 29.00              | 58.00                 |
| BS-800    | 26.00              | 52.00                 |

4.2 Load-Deflection Response and residual strength
The load-deflection curves for the test slabs are plotted in figure 7. It seems that the load-deflection response of the unexposed slab (BS-25) is totally different from the behaviors of other slabs experienced fire flame. The behavior of the BS-25 started with a stiff part, where the increase in the central-deflection was low with boosting the applied load. This part continued to a load of approximately 40 kN. Afterward, the second phase appeared, where the reading of central deflection climbed extremely without significant change in the applied load due to stiffness degradation resulting from cracks growth and enlarging; this part is known as a plastic plateau that explains the ductility of failure.

Concerning the fire-exposed slabs, the plastic plateau in their load-deflection responses became much shorter and got absent for slabs exposed to higher temperatures and failed in shear, as in the BS-800. Broadly, the burned slabs' responses were softer than the control one from the beginning until the end of the experiments. For example, at a load of 26 kN that is the smallest collapse load obtained in tests for the BS-800 slab, the burned slabs gave higher deflections than that of the control slab, by about 155%, 73%, and 36% for specimens BS-200, BS-500, and BS-800, respectively. There are several reasons made the burned slabs less stiffness, inclusive (1) the initiation of hair fire cracks after fire-exposing, (2) the weakness in the bond strength between steel bars and concrete, and (3) the ability of cracks to develop and get huge fastly throughout the burned concrete.

Finally, the burned slabs had residual strength in the range of 52% to 71.8% of the control slab, as stated in table 2 and figure 8. The loss in strength was raised as the fire flame temperatures elevated. This can be ascribed to the strength declines of principal components of slabs: steel and concrete with high temperatures in addition to the three reasons mentioned above.
4.3 Ductility
Ductility signifies a critical characteristic of the RC element, reflecting the ability to experience noticeable plastic deformations prior to collapse. Herein, the ductility indexes for all slabs were determined based on the approach of Spadea et al. [32]. The ductility is calculated as the total area ratio under the load-deflection response to a limited area stretched up to the service loads. The service loads were assumed to be 70% of the peak loads, as recommended previously in studies [33]. Table 3 reports these values; it can be observed that the ductility of voided slabs decayed due to exposure to high fire flame. The ductility indexes of BS-200, BS-500, and BS-800 slabs were 52.08%, 61.18%, and 65.97% below that of the unexposed slab BS-25, respectively. The ductility index depends mainly on the ultimate deflection at collapse, or in other words, on the length of the plastic plateau parts. As previously explained, the plastic plateau was decreased or even eliminated in slabs exposed to elevated temperatures owing to a pronounced descent in the concrete strength.

4.4 Service Stiffness
In order to discuss the influence of fire flame on the stiffness of voided slabs, the service stiffness was calculated for each one by determining the slope of a line, passing through two points situated on the rising part of the load-deflection response. These points match to 50% and 80% of the peak load [34]. This zone of the load-deflection response depicts the cracked section of behavior under realistic service loads. The calculated service stiffness values for each slab are listed in Table 3. It was found that the fire flame harmed the stiffness of voided slabs remarkably, where reductions of 30.29% - 54.18% were noticed for slabs burned at temperatures of 200 - 800 °C, respectively, when compared to the control slab BS-25. The causes leading to this stiffness deterioration were enumerated earlier in section 3.2.

4.5 Flexural Toughness
The flexural toughness was evaluated in Table 3 for each slab as the area under the load-deflection graph up to the ultimate deflection. This measure interprets RC members' capacity to absorb energy before failure, representing an essential structural feature for RC members to be constructed in a seismic area [35]. As shown in Table 3, once the voided slab had burned at a temperature of 200 °C, the slab ability to disperse energy downed to 60.55% relative to the control slab. After this temperature, the energy absorption of voided slabs continued to decrease, but at a lower rate. The toughness falls for slabs BS-500 and BS-800 were close, about 72.53% and 77.82% smaller than that of the BS-25, respectively. The toughness of any RC element depends chiefly on concrete to resist both cracking and crushing. Due to fire exposure, the concrete strength dropped significantly; accordingly, its ability to withstand such
deformations became slight, leading to a reduction in the flexural stiffness compared to the unburned slab.

| Specimens | Ductility factor (D.F) | Service stiffness (kN/mm) | Flexural toughness (kN.mm) | % Decrease in ductility factor | % Decrease in service stiffness | % Decrease in flexural toughness |
|-----------|------------------------|---------------------------|---------------------------|-------------------------------|-------------------------------|-------------------------------|
| BS-25     | 6.26                   | 20.47                     | 193.53                    | ---                           | ---                           | ---                           |
| BS-200    | 2.99                   | 14.27                     | 62.81                     | 52.08                         | 30.29                         | 60.55                         |
| BS-500    | 2.43                   | 10.79                     | 53.17                     | 61.18                         | 47.29                         | 72.53                         |
| BS-800    | 2.13                   | 9.38                      | 42.92                     | 65.97                         | 54.18                         | 77.82                         |

5. Conclusions
Depending on the performed experimental program, the most salient results can be summarized as follows:

- The failure mode was found to be altered from the combined flexural-shear to more brittle shear mode when the voided slabs were subjected to temperatures greater than 200 °C.
- The unexposed slabs showed an entirely dissimilar load-deflection curve compared to burned slabs. In this slab, the plastic plateau was apparent, while in others, this part of the load-deflection response was much smaller or even lacking, as happened in the slab burned at 800 °C.
- The strength of voided slabs dropped significantly because of fire flame. Compared to the unburned control slab, the reductions in strength for slabs exposed to 200 °C, 500 °C, and 800 °C touched 28.2%, 42%, and 48%, respectively.
- The other mechanical features of slabs, including ductility, service stiffness, and toughness, also declined as a consequence of fire exposure. The drops in these characteristics were in a range of 52.08%-65.97%, 30.29%-54.18%, and 60.55%-77.82% for slabs burned at 200 °C-800 °C, compared to the unburned slab, respectively.

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