Bubble slabs burned at 800 °C with different periods

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Abstract. The bubble slabs are a modern type invented to reduce the self-weight significantly. However, limited studies were conducted on such slabs, and many influencing parameters still uninspected or need further investigations. The period of fire flame exposure is one of these factors. Hence, the current study was planned to examine bubble slabs’ behavior when burned at 800 °C for different durations. Four bubble slabs were designed in analogous specifics. Three slabs were exposed to direct fire flame of 800 °C for three durations: 1, 1.5, and 2 hours. The remaining one was kept without exposure. Just the burning operations had accomplished, the slabs were statically tested under the influence of uniform loads. The results indicated that exposed slabs’ failure mode changed to the shear mode, and the flexural cracks were limited. The slabs’ strengths decreased owing to fire flame, where the residual strength of burned slabs were 50.24%–20.78% of that of the control slabs. Besides, essential decays in the mechanical characteristics of burned slabs were observed compared to the control one.

1. Introduction

Bubble slabs are a modern type of slabs developed in 1990 by Danish engineer Jorgen Breuning to minimize the self-weight of slabs meaningfully up to 35%. The reduction in the self-weight is the result of eliminating an enormous concrete volume by introducing voids in the middle of slabs' depth between the upper and lower reinforcement meshes [1]. These slabs are an economical construction system because of materials-saving and the need for smaller supporting elements (columns and footings). They are also environmentally friendly due to the decline in the air pollutants emitted from the cement industry [2]. Numerous investigations were implemented on bubble slabs [3–6]. The studies first inspected their flexural strength, and the results reported a slight fall in the flexural strength of such slabs relative to those having a solid cross-section area. This conclusion did not apply to shear strength, where notable decays were addressed, reaching 27-40% compared to solid slabs' shear strength [7].

Investigators [8,9] have then focused their attention on the bubble slabs' punching strength. They announced that when the voids were placed within the critical zone near the columns, the punching strength of bubble slabs dropped to a large extent, and therefore, these voids should be positioned beyond this zone [10]. According to the outcomes of Schnellenbach-Held et al.[11], placing the voids at a distance equal to half the effective depth of slabs, apart from the columns, was efficient in developing the punching strength to touch the same that of the solid slab. Nevertheless, an inconsistent statement was described in other studies [12,13], where 35-50% decays in the punching strength of voided slabs were observed even though the voids were shifted at a spacing of 1.5 the slab thickness from the column perimeter.
Fire accidents are serious encounters facing the reinforced concrete (RC) structures. Hence, all buildings' elements should be designed to be satisfactorily fire-resistant to prevent sudden failure. Due to the large area, the slabs will be the most affected member in the event of a fire in the building. Generally, concrete is accurately resistible to fire because of several characteristics, such as negligible thermal conductivity and brilliant thermal aptitude [14,15]. In spite of these physical characteristics, a noteworthy difference in concrete mechanical features was registered consequent to severe microstructural reform related to intense fire flames [16]. Fire damage in RC elements relates to variables, including fire scenarios, features of raw materials, and the degree of restriction [17,18]. Formerly, the influence of fire on RC elements was considered by several attempts. Concerning slabs, the heat was discovered to transfer through all dimensions because of their semi-infinite sides [19,20]. Moreover, two-way slabs were more resistible to high temperatures than those rested in one-way form due to membrane action [21]. Likewise, slabs' behavior with a hollowed cross-sectional area was more complicated in the fire than solid slabs due to hollows that make the transmission of heat terminate across the slabs’ depth [22].

Waryosh and Hashim [23] performed an investigational schedule on seven bubble slabs burned up to 400 °C as a maximum. Then, the fire-damaged slabs were retrofitted via CFRP. They illustrated that once fire temperature had passed 300 °C, the concrete spalling off appeared. Also, the use of CFRP in the strengthening of the deteriorated specimens enhanced the load-carrying capacity of slabs to be 88-105% of that of the unburned slab.

Based on the reviewed literature, the information about the voided slabs’ behavior in fire or high temperature is insufficient, particularly about the exposure periods. Hence, this study was directed to inspect the influence of fire durations on the voided slabs. Four bubble slabs were fabricated and then subjected to 800 °C direct fire flame with various exposure periods (1, 1.5, and 2 hours). One slab was kept without burning as a reference sample. All slabs were afterward tested by applying uniformly distributed loads. The results were discussed and compared to show the fire period's impact on bubble slabs’ mechanical features, including strength, deformations, ductility, toughness, and stiffness.

2. Experimental program

2.1 Test specimens and burning processes

Four similar bubble slabs, measuring 500 mm×270 mm×90 mm, were made and reinforced, as shown in Figures 1 and 2. As seen, the details of reinforcement were identical for upper and lower meshes, where six and ten bars of 4 mm diameter were used in the longitudinal and transverse directions, respectively. These bars had a yield strength of 508 MPa. The voids were created inside the slabs by implanting 15-70 mm diameter-plastic balls in the center of the slabs amid the reinforcement meshes, as illuminated in Figure 1 and plotted in figure 2. All slabs were fabricated using one concrete batch, having the weight mix design of 1 (cement):1.77 (gravel):2.22 (sand); the water to cement ratio was 0.55. the employed cement was ordinary Portland cement, and the aggregates were prepared and washed. The coarse aggregates were crushed, with a peak size of 8 mm. escorted by each slab, three 150 mm cubes were manufactured. Slabs and supplemented cubes were then placed in tubs filled with water for 27 days, one day after completing the casting process; the mean obtained concrete compressive strength at 28 days was 24.8 MPa according to tests performed on the 12 cubes.

In order to achieve the study aim, three slabs were subjected to 800 °C direct fire flame, but in different exposure times, which were 1, 1.5, and 2 hours; one slab was kept unburned as a control specimen. A 770 mm×520 mm×450 mm size diesel furnace (figure 3) was utilized in burning the bubble slabs. The fire flame was increased at a rate of 100 °C/minute. After the planned fire scenario had accomplished, the samples were cooled down slowly inside the furnace. Table 1 reports the details of considered slabs; as displayed, the slabs were labeled by designations, starting with letters of VS that referred to the voided slabs tailed by a number, declaring the fire periods in hours.

Finally, the burned slabs accompanied by the control one were tested under uniformly distributed loads up to the time of failure; the loads were applied incrementally by a hydraulic jack into a steel plate, on which the sandbag was rested. The compression face of slabs were placed on this sandbag, and hence,
a uniform load was expected to realize via this sandbag. Figure 4 illustrates how uniform loads were subjected; as explained in this figure, the slabs were supported simply inside the testing machine, with a supporting length of 450 mm. Besides, a single dial gauge was placed at the mid-span of the slabs, touching their tension faces to record the peak deflection that was expected to occur at these points.

**Figure 1.** Photograph of specimen setup.

**Figure 2.** Locations of steel reinforcement and the plastic balls.

**Figure 3.** Used diesel furnace in tested.

**Figure 4.** Test setup.

**Table 1.** Details of the test bubble slabs.

| Slab designation | Thickness (mm) | Temperature (°C) | Exposure time (hour) |
|------------------|---------------|------------------|---------------------|
| VS               | 90            | -                | -                   |
| VS-1             | 90            | 800              | 1                   |
| VS-1.5           | 90            | 800              | 1.5                 |
| VS-2             | 90            | 800              | 2                   |
3. Test Results

3.1 Cracking Patterns and Failure Modes

The unburned control sample VS slab cracked early at its mid-span, where the flexural stresses were maximum. The cracking load was approximately 30% of the failure force. The intensity of cracks subsequently soared, while the uniformly distributed load was furthered. At a 40 kN force, abundantly of cracks were observed; these cracks spread along the slab span and widened apparently. Close to collapse, diagonal cracks started to occur near the roller supports; they developed quickly and was the main reason for failure. The failure mode was combined flexural-shear, as stated in Figures 5 and 6.

Regarding the fire-exposed slabs, the observation of cracks initiation was difficult due to the manifestation of capillary cracks stated in Figure 7 that distributed haphazardly on the exposed faces of slabs instantly after the burning operations. These cracks were more visible and deep for samples exposed for long periods to the flame of fire. Broadly, the burned specimens did not show obvious flexural cracks, while the diagonal ones developed fastly and premature, making these specimen got a brittle failure due to shear mode, as demonstrated in figure 8. The concrete strength is the crucial parameter in determining the shear strength of slabs [24,25], where the web reinforcement is typically not provided. Hence, the shear mode was the governing failure for fire-exposed slabs since the concrete strength significantly dropped when exposed to intense fire flame. The ultimate loads, residual strength, and failure mode of tested specimens are listed in Table 2.

| Specimens | Ultimate load (kN) | Residual strength* (%) | Mode of failure        |
|-----------|--------------------|------------------------|------------------------|
| VS        | 49.76              | 100.00                 | Combined flexural-shear|
| VS-1      | 25.9               | 50.24                  | Shear failure          |
| VS-1.5    | 13.9               | 28.05                  | Shear failure          |
| VS-2      | 10.34              | 20.78                  | Shear failure          |

*Residual strength = strength of the burned specimen/ strength of the reference slab.

3.2 Load-Deflection Response and Residual Strength

The influence of exposure to 800 °C temperature with different durations on the load-deflection response of bubble slabs is plotted in Figure 9. This drawing clearly shows that exposure to a direct fire flame led to a radical change in the bubble slab's behavior. The bubble slab VS gave a load-deflection response distinguished without fire exposure by being split into three distinct phases. The first phase was the stiffest in which the increase in the deflection was relatively slight with the load progress; this part lasted until the cracking attendance. The second segment then took place, where the increment rate for registered deflection versus the applied loads was higher than that noted previously due to stiffness deterioration resulted from the cracking development. This region continued up to 42 kN, about 84% of the ultimate strength. Subsequently, the third phase appeared in which the stiffness decay reached its climax consequent to the vast cracks the developed along the entire length and across the full depth of the slab. Accordingly, the central deflection increased significantly up to 5.2 mm against trivial augmentation in the applied load; this segment is identified structurally as a plastic plateau behavior.

The upper illustrated behavior was not appreciated for burned slabs, where the plastic plateau was completely inattentive. On top of that, these specimens showed soft responses (i.e., large deflection versus very slight loads) from the test start because of scattering hair cracks on their faces directly beyond the fire exposure. The softness in the load-deflection responses became more obvious as the exposure time to fire flame was lengthened.

The previous studies conducted on RC members' fire resistance illustrated that both steel bars and concrete lose a substantial amount of their strength due to fire-exposure, especially when the temperature is more than 500 °C [26,27]. The initiation of fire hair cracks also weakens the bond strength between bars and concrete. These causes gathered made the strength of bubble slabs burned to 800 °C dropped
fundamentally. These slabs' residual strengths exposed to 1, 1.5, 2 hours were 50.24%, 28.05%, and 20.78% of the unburned control slab's peak strength, correspondingly, as shown in figure 10.

![Figure 5. Cracking pattern of specimen VS. at failure.](image1)

![Figure 6. Formation and development of the diagonal crack before failure.](image2)

![Figure 7. The spread of random cracks on the surfaces of the burning slabs.](image3)

![Figure 8. Cracking pattern of specimen VS-1 at failure.](image4)

![Figure. 9 Load-contrail deflection relationships of the tested specimens.](image5)

![Figure. 10 The percentage of residual strength versus exposure time.](image6)

3.3 Ductility
RC elements should be designed with a sufficient ductility index to prevent sudden failure. Therefore, it is important to evaluate the fire period's influence on such a parameter that reflects the members' potentiality to display huge deformations before the collapse. Herein, the method developed by Spadea et al.[28] was implemented to calculate the ductility index. This method depends entirely on the area
under the load-deflection response, and the ductility is assumed as a percentage of the fractional area extended to the service load to the full area. The service loads were supposed to be 70% of the corresponding ultimate load, following the outlines of former investigations [29–33]. The determined ductility indexes are reported in Table 3 for all tested slabs. It can be seen from the records of Table 3 that the exposure to 800 ºC fire flame reduced the ductility of the VS-1 slab sharply to 59.33%, compared to the control VS slab. For more extended periods, the ductility index continued to decrease, but at a lower rate to arrive near percentage, about 71.26%, and 74.96%, for specimens burned for 1.5 and 2 hours, respectively, below that of the VS slab.

3.4 Service Stiffness and Secant Stiffness
It is interesting to explore the impact of fire durations on the structural responses of voided slabs. In the current study, the decays in both service and secant stiffnesses due to fire flame were assessed. Service stiffness was measured as the slope of a line, drawn from two points located on the load-deflections graphs of slabs. These points parallel to 50% and 80% of the peak load [34]. The secant stiffness was also a slope of a line but extended from the origin point of the load-deflection response to that of peak load [17]. The determined values are listed in Table 3. This table states that both stiffness types were reduced due to the fire flame's high temperature, and the service stiffness was the most influenced. There are two reasons for these declines, which were the reduction in inertia moments of burned slabs due to initiating the fire hair cracks that made the development of flexural and shear cracks more quick and apparent, while the second cause was the drop in the concrete modulus of elasticity resulted from slight concrete strength of fire-exposed specimens. The decays of service and secant stiffness were in a range of (54.20%, 77.01%, and 80.76%), and (36.37%, 49.69%, and 68.24%) for slabs exposed for (1, 1.5, 2) hours, respectively, compared to the unburned slab.

| Specimens | Ductility factor (D.F) | Service stiffness (kN/mm) | Secant Stiffness (kN/mm) | Flexural toughness (kN.mm) | % Decrease in ductility factor | % Decrease in service stiffness | % Decrease in Secant stiffness | % Decrease in flexural toughness |
|-----------|------------------------|---------------------------|--------------------------|---------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| VS        | 5.95                   | 20.48                     | 9.76                     | 183.90                    | ---                           | ---                           | ---                           | ---                           |
| VS-1      | 2.42                   | 9.38                      | 6.21                     | 42.91                     | 59.33                         | 54.20                         | 36.37                         | 76.67                         |
| VS-1.5    | 1.71                   | 4.71                      | 4.91                     | 23.11                     | 71.26                         | 77.01                         | 49.69                         | 87.44                         |
| VS-2      | 1.49                   | 3.94                      | 3.10                     | 15.39                     | 74.96                         | 80.76                         | 68.24                         | 91.63                         |

3.5 Flexural Toughness
Flexural toughness is a structural feature of RC elements, denoting the total energy absorbed by them till failure [35,36]; this feature can be determined via cumulating the area beneath the load-deflection graphs. This characteristic is significant for elements being constructed within zones expected to expose dynamic loads, such as seismic or blast. Accordingly, it is necessary to examine the effect of flame times on this property. Table 3 lists the calculated flexural stiffness for the four slabs. The table indicates that the voided slabs lost a remarkable amount of flexural stiffness consequent to high temperatures for different periods. Compared to the VS slab, declines were 76.67%, 87.44%, and 91.63% for bubble slabs burned for 1, 1.5, and 2 hours, respectively. The resistance of concrete to cracking and crushing is the core factor in recounting the RC members' toughness. Due to exposure to fire flame, especially at a high temperature of more than 150 ºC, this resistance deteriorates appreciably because of the microstructural change in the burned concrete [17]. This reason explains why the burned slabs forfeited significant toughness percentages relative to the control unexposed slab.
4. Conclusions
This paper aimed to assess the impact of high fire flame periods on structural responses of bubble slabs. Therefore, four bubble slabs were fabricated; three specimens were burned at 800 °C by direct fire flame for 1, 1.5, and 2 hours. All slabs were then tested by subjecting uniformly distributed loads. Compared to the unburned control slabs, the main influences of fire durations on bubble slabs could be abbreviated as follows:

- The exposure to a fire flame of 800 °C for any period made the bubble slabs failed brittlely in shear instead of the combined flexural-shear mode noted for the control slab.
- The load-deflection graphs of burned slabs lacked the plastic plateau phase in contrast to the control slab due to shear failure mode.
- The load-carrying capacities of bubble slabs were highly decayed because of the fire flame. The decay became more significant as the fire period was extended. Compared to the unexposed slabs, the residual strengths of exposed slabs for 1-2 hours were 50.24%-20.78%, respectively.
- Burning at 800 °C for 1-2 hours resulted in declines in the mechanical properties of bubble slabs. Compared to the control slab kept without exposing, the deteriorations in the ductility, service stiffness, secant stiffness, and flexural toughness of slabs exposed for 1-2 hours approached 59.33%-74.96%, 54.20%-80.76%, 36.37%-68.24%, and 76.67%-91.63%, respectively.

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