Structural Performance of Reinforced Concrete Bubble Slabs after Exposing to Fire Flame

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Abstract:

This paper presents the results of experimental program investigating the effect of fire flame (high temperature) on the structural performance of bubble slabs. The program consisted casting and testing nine specimens. The dimensions of the specimens were 270 X 500mm in plane and with two different thicknesses; 90 and 140mm. All specimens were cast with normal concrete of approximately 25 MPa compressive strength. Seven specimens were burnt using a diesel furnace and two specimens were kept without burning as controls. The test parameters were; the fire flame temperature (200, 500, and 800 °C), the cooling method is processed gradually by left the slabs in the air or suddenly by using water, the exposure time (1, 1.5, and 2 hours), and thickness of slabs (90 and 140mm). After cooling, the specimens were simply supported in one direction and tested under a uniform load applied gradually till failure. The test results showed that, the residual strength of specimens decreased from 71.8% to 21.6% and their central deflection increased with increasing the fire flame temperature from 200 to 800 °C and exposure time from 1 to 2 hours. For suddenly cooling specimen the residual flexural strength and central deflection were less than those of same specimen when cooled gradually. Finally, increasing the thickness of bubble slabs by 56% improved distinctly both the residual strength about 45% and stiffness of specimens.

Key words: Bubble slabs, Temperature, Burning, Exposure time, Fire flame.

الاداء الانشائي للبلاطات الخرسانية المسلحة والمجوفة بعد التعرض الى لهب النار

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الخلاصة :

يقدم هذا البحث نتائج البرنامج العملي لتحري تأثير الحرق بدرجات عاليه بلهب النار على الاداء الانشائي للبلاطات الخرسانيه المسلحه المجوفه. تضمن البرنامج انشاء وفحص تسعه نماذج. أبعاد النماذج كانت 500 ملم طول و 270 ملم عرض و السمك اما 90 ملم او 140 ملم . جميع النماذج انشأت من خرسانه اعتياديه ذات مقاومه انضغاط 25 ميكا باسكال.

سبع نماذج تم حرقها بأستخ دام فرن نفطي واثنان تم حفظهما بدون حرق للمقارنة . العوامل التي تم دراسة تأثيه ا في هذا البحث كانت : درجة الحرق (200 و 500 و800 م) ، طريقة التبريد (تبريد تدريجي بترك النماذج في الهواء او تبريد فجائي باستخدام الماء)، فترة التعرض (1و1.5 و 2 ساعة) واخيراً سمك البلاطه (90 ملم او 140 ملم). بعد انتهاء عمليه تبريد النماذج ، أسندت النماذج بشكل بسيط من أتجاه واحد وفحصت تحت تأثير حمل منتشر تم تسليط ذلك الحمل بصوره تدريجي الى درجة الفشل . بينت نتائج البحث ان المقاومه المتبقيه للنماذج انخفضت من 71,8% الى 21.6% والهطول في منتصف النماذج أزداد مع ازدياد كلا من درجه الحرق من 200 الى 800 مْ وفترة التعرض من 1 الى 2 ساعه . المقاومة المتبقي والهطول للنموذج المبرد بشكل فجائي كانت اقل من النموذج المبرد بشكل تدريجي واخيراً أن الزياده في سمك البلاطه بمقدار 56% ادى الى تحسين ملحوظ في كلاً من المقاومة المتبقيه (بمقدار 45 %)وصلابة العينات.

1. Introduction:

In building constructions, the slab is a very important structural member to make a space. And the slab is one of the largest member consuming concrete [1]. In a general way, the slab was designed only to resist vertical load. However, as people are getting more interest of residential environment recently, noise and vibration of slab are getting more important [2]. In addition, as the span is increased, the deflection of the slab is also increased. Therefore, the slab thickness should be increase. Increasing the slab thickness makes the slabs heavier, and will increased column and foundations size. Thus, it makes buildings consuming more materials such as concrete and steel reinforcement [3]. To avoid these disadvantages which were caused by increasing of self-weight of slabs, the Bubble Deck slab system, also known as void slab, was suggested. This system consists of hollow plastic spheres putting into the concrete to create a grid of void forms inside the slab. Large span concrete flat-slab systems with internal spherical void formers (SVF) have been used in Europe for over a decade [4].

The Bubble Deck combines the advantages of material- saving and extreme load-carrying capacity because of its optimized cross-section. The reduction of the dead load is about 30%. The principle of this slab is to connect hollow plastic balls (bubbles) with reinforcing elements in an industrial prefabrication phase, which leads to a more efficient method of construction [5].

Calin et al. [6] in 2010, constructed and tested one full scale bubble slab under uniform loading. In same year, Marais et al [4], investigated experimentally the shear resistance, and short-term elastic deflections of Spherical void formers slabs.

Ibrahim et al. [7] in 2012, tested six half-scale bubble slabs under a five point- load system to study the flexural capacities of R.C two way hollow slabs of plastic spherical voids. In 2014, Churakov[8] ,presented the different types of bubble slabs , reviewed their advantages over the ordinary solid slabs and demonstrated the most famous of present examples of this new technology.

However, this paper is experimental study of bubble slabs exposed to fire flame.

2. Research Significance:

Sustainability of structures is a main concern in the construction industry. Exposure to fire flame is an extreme condition that leads to change in materials properties, consequently, change in overall behavior is expected. Many research efforts were devoted toward evaluation of materials' performance when exposed to fire and high temperature events. These efforts provide understanding to the change of the materials properties and recommend guidelines to enhance preference in such events. Therefore, the objective of this paper is to highlight the differences in behavior of reinforced concrete bubble slabs when exposed to fire flame.

3. Test Specimens and Burning Processes:

Nine reinforced concrete bubble slabs with 500mm length and 270mm width were constructed. Two of them had 140mm thickness and others had 90mm thickness. All slabs were reinforced in two layers at top and bottom, each layer composed of 6-ϕ4 in long direction and 10-ϕ4 in short direction. The reinforcing steel bars were deformed bars with a yield strength of 508MPa. Fifteen bubbles were created inside each slab using plastic balls of 70mm diameters, as shown in Fig. (1).

The nine specimens were cast with one concrete batch, Ordinary Portland cement was used with washed sand and graded crushed coarse aggregates of 10 mm maximum size. The proportions by weight of cement: sand: aggregate were 1.00:1.77:2.22 with a water/cement ratio of about 0.55. The average 28-day cylinder compressive strength obtained was 24.8 MPa. After casting, the specimens were covered with polythene sheets and after 14 hours they stripped of the moulds and placed in water tank for 27-days and then burned.

For seven specimens of 90mm thickness, three of them were burned by fire flame to 200 °C, 500 °C, and 800 °C, respectively for one hour, and then cooled slowly by left them in the open air. Two specimens were exposed to fire flame temperature 800 °C for 1.5, and 2 hours, respectively, and then cooled freely in the open air. The remaining specimens, one did not expose to fire and kept as control specimen and the other was subjected to temperature 800 °C for one hour and cooled suddenly by spraying with water.

For two specimens of 140mm thickness, one was kept as control without burning. The remaining one was burned by fire flame temperature 800 °C for one hour and then cooled freely in the open air.

The burned specimens are identified by four symbols. The first symbol refers to the thickness of slabs, the letters S. and L refer to smaller thickness (90mm) and larger thickness (140mm), respectively. The second symbol is a number: 2, 5, and8 referring to burning temperatures 200 °C, 500 °C, and 800 °C, respectively. The third symbol refers to the fire exposure time in hours (1, 1.5, and 2). The fourth symbol (G or S) refers to the cooling method (gradually or suddenly). Finally, the two control specimens are named as L for slab with 140mm thickness and S for slab with 90mm thickness. The details of specimens considered in this study are listed in Table (1).

The burning processes were performed in a welding workshop of the College of Engineering at Wasit University. A diesel furnace, with dimensions of 77 cm length, 52cm width, and 45cm height, was used. The furnace has a digital monitor to record the degree of temperature inside it as shown in Fig.(2).

During the burning processes, the plastic balls burned inside specimens exposed to fire temperature greater than 200 °C, and the fire flames exited from it and penetrated the cover of slabs, Figs. (2 and 3). After the cooling of specimens, many cracks were obvious on the surface of the specimens, their depth and intensity increased as the fire flame temperature and exposure time increased as shown in Fig.(3) . However, the thicker slab (140mm thickness) showed cracks with intensity smaller than the thinner slab (90mm thickness) exposed to the same fire temperature.

The external skin of specimen exposed to 800 °C was spall off when it cooled suddenly by water splash, as shown in Fig. (4). This is because the rate of increasing temperature was less than that of decreasing temperature and led to worse effect on the interfacial bond between the concrete components.

Due to hydration of iron oxide component and other mineral of cement and the aggregate, the color of the concrete changed to pink [9].

Table (1) Details of reinforced concrete bubble slabs.

Slab designation	Thickness (mm)	Temperature (°C)	Exposure time (hour)	Method of cooling
S	90	-	-	-
S21G	90	200	1	gradual
S51G	90	500	1	gradual
S81G	90	800	1	gradual
S81.5G	90	800	1.5	gradual
S82G	90	800	2	gradual
S81S	90	800	1.5	Sudden
L	140	-	-	-
L81G	140	800	1	gradual

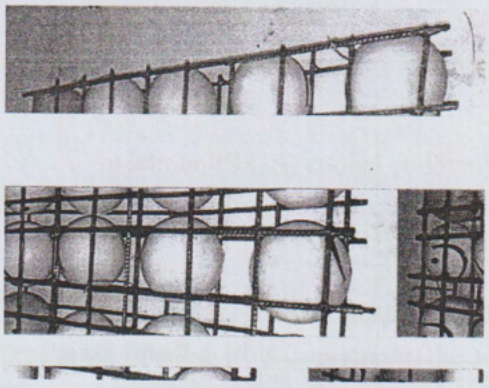


Fig.(1) Arrangement of Reinforcement and Plastic Balls inside Specimens.

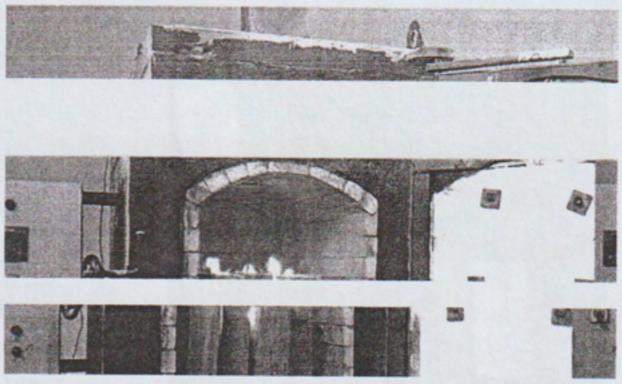


Fig.(2) Burning of Specimens inside The Diesel Furnace.

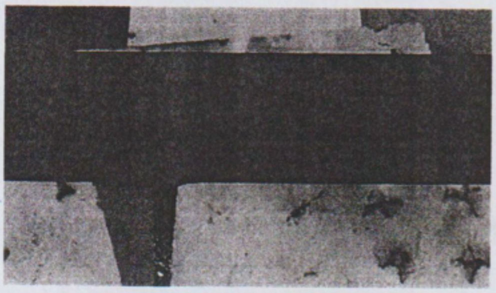


Fig.(3) Cracking of Specimens just After Cooling.

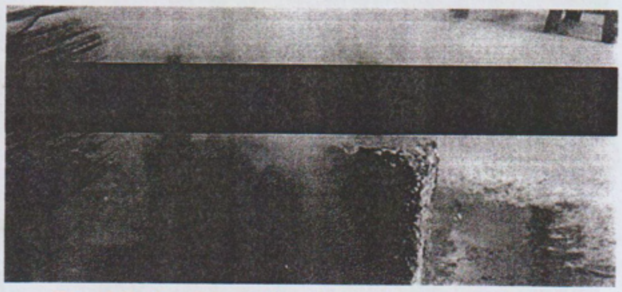
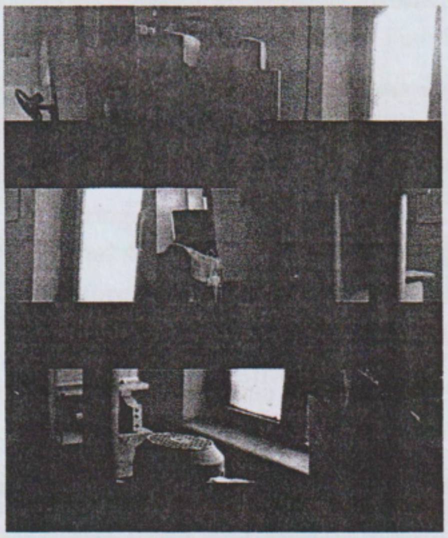


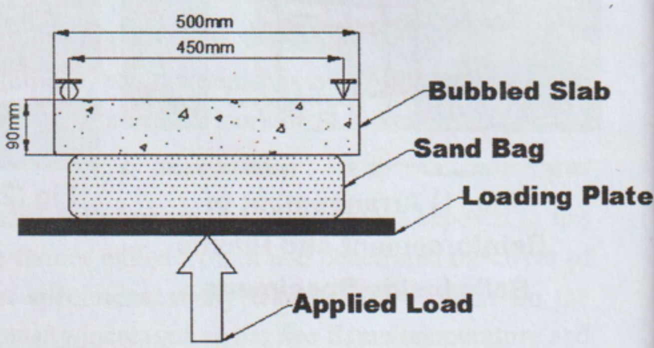
Fig.(4) Sudden Cooling for Specimen Exposed to 800°C Temperature.

3. Testing Procedure:

After cooling of specimens, they were kept at concrete laboratory for one-day and then tested under a uniform loading. The uniform loading was achieved using a sand bag between the loading plate of the testing machine and the compression face of the specimens as shown in Fig. (5a). The test specimens were simply supported on long direction only, with supported length of 450mm center to center. The load was applied gradually till failure of the specimens. After each load increment, the deflection reading at mid span of the specimens was recorded using digital dial gages of accuracy of (0.01mm), and cracks propagation were marked. Fig. (5b) shows the schematic diagram of the test set up.



(a) Photograph of Test Setup



(b) Schematic of Test Setup

Fig.(5) Test Setup

4. Test Results and Discussion:

4.1. Crack Patterns and Failure Modes:

For specimens with 90mm thickness, both control specimen (S) and burnt specimen at 200 °C (S21G) exhibited a diagonal tension failure. In which, the flexural cracks were first to develop at the mid of the span where the bending moment was maximum and the shear was zero. As the external load increased, additional cracks occurred and spread along the middle third of span, and the initial cracks widened and extended deeper toward the neutral axis and beyond. At failure, diagonal shear cracks were initiated near the supports and propagated toward the compression surface of the specimens as illustrated in Fig.(6a).

When the fire flame temperature exceeded 200 °C for specimens (S51G, S81G, S81.5G, and S82G), the mode of failure changed to pure shear failure by forming one or more inclined cracks close to the supports as illustrated in Fig.(6b). Because the strength of concrete decreased rapidly when the fire temperature exceeded 300 °C[10]. The shear strength of the slabs depends significantly on the concrete compressive strength. In this failure mode, the intensity of flexural cracks was less than that of diagonal tension failure and they extend below the neutral axis.

Specimen (S81S) cooled suddenly by spraying with water did not show a clear cracks because of spalling off of the external skin and failed in brittle mode by crushing the concrete, Fig.(6c).

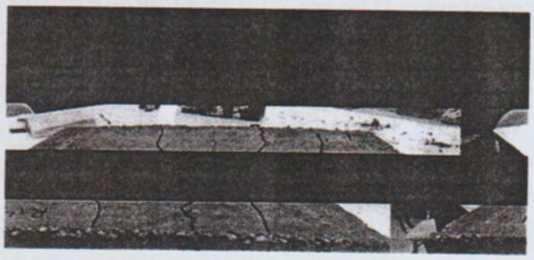
Slabs with 140mm thickness (control and burnt) failed by shear, where one inclined cracks developed from support to the upper slab face, Fig. (6d). This mode was expected because of a small shear span to depth ratio.

After the completion of the test, some of specimens were smashed using an ax to see what happened inside it. All plastic balls were completely burned as shown in Fig. (6 e).

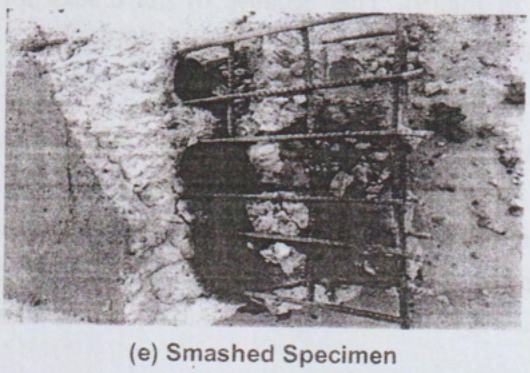
(a) Cracking Pattern of Specimen (S)

(b) Cracking Pattern of Specimen (S81G)

(c) Cracking Pattern of Specimen (S81C)



(d) Cracking Pattern of Specimen (L)



(e) Smashed Specimen

Fig.(6) Cracking Patterns of Specimens at Failure

4.2. Residual Strength:

The nine specimens are grouped, as listed in Table (2), to study the effect of fire frame temperature, time of exposure, rate of cooling, and slab thickness on the residual strength of specimens exposed to fire flame.

Table (2) and Fig.(7) show that, the ultimate load capacity for specimens of group 1(which had thickness of 90mm , exposed to fire for 1 hour and gradually cooled) decreased with increasing the fire flame temperature. The residual strength were 71.8%, 58%, and52% for specimens exposed to fire flame temperature 200 °C, 500 °C, and 800 °C, respectively. However, the residual strength for specimen of 140mm thickness burned at 800 °C and gradually cooled was 69.4%. The reduction in the residual strength of the specimens can be attributed to the several factors, the first factor is the fact that the cracks formation and growing increased inside the specimens as the temperature increased as a result of evaporation of free moisture in the concrete, this led to decrease the bond strength between the concrete components as well as the concrete and the reinforcement bars. The second is the exiting of restricted air in the bubbles due to the fully burning of the plastic balls causing formation of big voids inside the slabs with circumference cracks around them, these voids did not contribute in the strength of slabs. The final factor is the steel expanded at high temperature and the concrete shrank at same time [11].

The exposure time to fire flame has a significant effect on the residual strength of specimens. The residual strength for specimens exposed to 800 °C for 1, 1.5, and 2 hours and gradually cooled (group 2) were 52%, 27.6% and 21.6%, respectively. Fig.(8) shows a high decline rate in the residual strength of specimens when the exposure time increased to 1.5hour, for longer time , the residual strength continued to decrease at lower rate. This means that, the most components of the reinforced concrete bubble slabs were damaged when exposed to fire flame for 1.5 hour.

The ultimate load capacity of specimen exposed to fire flame temperature 800 °C for one hour and cooled freely was larger than that of the same specimen cooled suddenly, by about 13%, as shown in Fig.(9). This because of the cracks formation and propagation increased with increasing the rate of cooling, due to the difference in temperature between the inner and outer concrete during the processes of burning and cooling.

Increasing the thickness of slab from 90 mm to 140mm, about 55.6% increasing in thickness, enhanced the ultimate load capacity of specimens burned at 800 °C for 1 hour by 45%. However, the increase in the ultimate load was little for control specimens, without burning, about 7.8%, because of brittle failure (shear failure) of specimen L (140mm thickness) comparing with specimen S (90mm thickness) which failed in combined shear and flexural.

Table (2) Specimens Test Results.

No of group	Purpose of group	Specimen	Thickness (mm)	Temperature (°C)	Exposure time (hour)	Type of cooling	Ultimate load (kN)	Residual strength* (%)
1	Effect of fire flame temperature	S(control)	90	0	1	gradually	50.00	100.00
		S21G		200			35.90	71.80
		S51G		500			29.00	58.00
		S81G		800			26.00	52.00
		L(control)	140	0			53.90	100.00
		L81G		800			37.70	69.94
2	Effect of time exposure	S(control)	90	800	0	gradually	50.00	100.00
		S81G			1		26.00	52.00
		S81.5G			1.5		13.80	27.60
		S82G			2		10.80	21.60
3	Effect of cooling method	S(control)	90	800	1	-------	50.00	100.00
		S81G				gradually	26.00	52.00
		S81S				suddenly	23.00	46.00

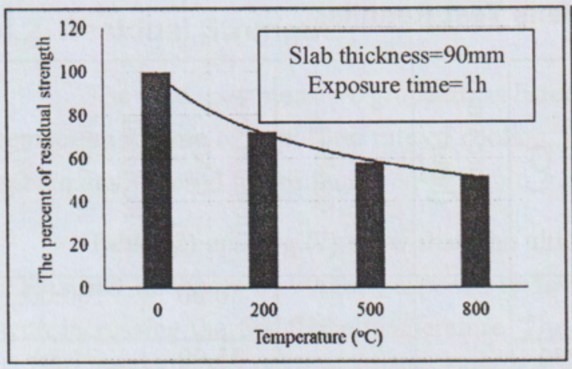


Fig.(7) The Percentage of Residual Strength versus Temperature

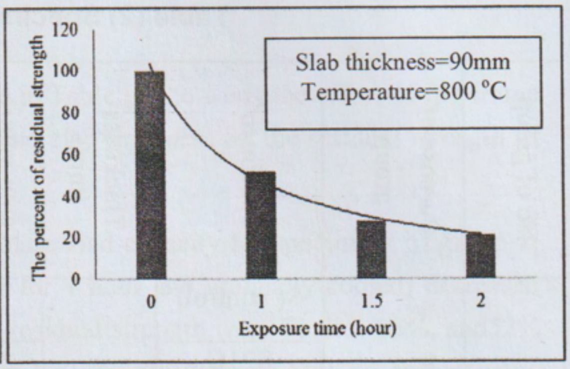


Fig.(8) The Percentage of Residual Strength versus Exposure Time

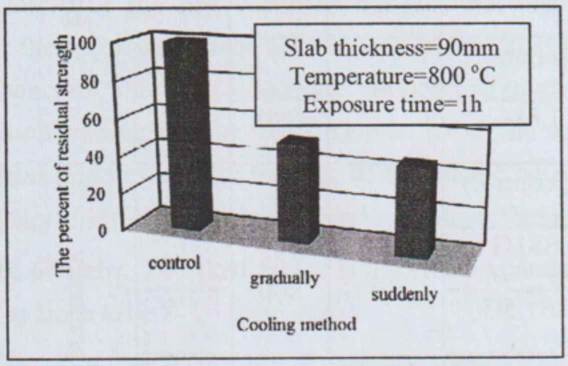


Fig.(9) The Percentage of Residual Strength versus Cooling Method

4.3. Load-Deflection Response:

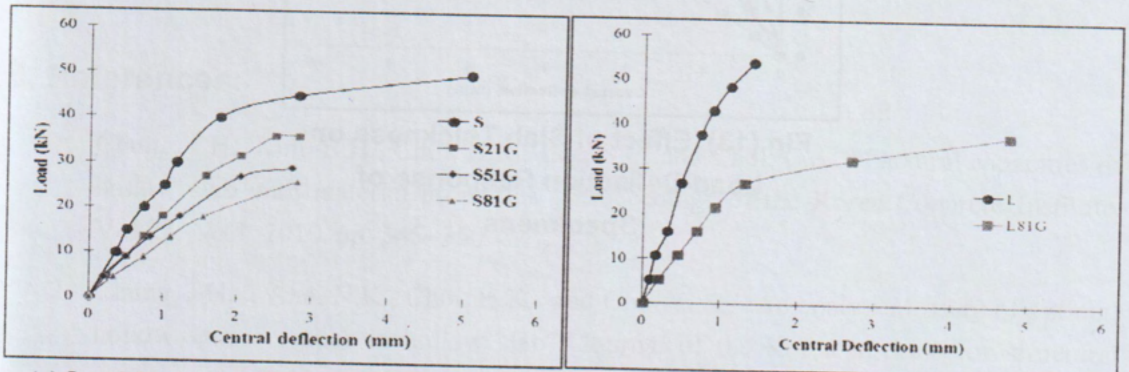
The influences of fire flame temperature, exposure time, method of cooling, and slab thickness on the load-deflection response of reinforced concrete bubble one way slabs are plotted in Figs. (10) through (13). The deflection was recorded at each load increment till failure at the center of the specimens where the maximum deflection was expected to occur.

The increase in the fire temperature has a significant effect on the central deflection of slab specimens of 90 and 140mm thicknesses, it can be noted from Fig.(10) that the increase in fire temperature increases the central deflection of specimens. In other words, the greater fire temperature give greater deflection values recorded for same load value. This means that specimens' stiffness decreased with increasing the fire temperature due to the reduction in the modulus of elasticity of concrete and the reduction in the effect section due to cracking resulted from the burning processes.

Fig.(11) shows a comparison between the deflection values recorded for specimens of 90mm thickness , exposed to fire temperature 800 °C for 1, 1.5, and 2 hours and then cooled freely with deflection values recorded for control specimen (S). At same load, the deflection values were greater for burnt specimens than that of control specimen, and the deflection value increased as the exposure time increased. Generally, the load-deflection responses for specimens exposed to fire flame for 1.5 and 2 hours are approximately convergent and linearly.

For load greater than 5 kN, the slab(S81S) exposed to temperature 800 °C and cooled suddenly by spraying with water gave stiffer load-deflection response than that of same specimen(S81G) cooled freely by open air, see Fig.(12). This is because of brittle failure of specimen (S81S) due to crush of concrete.

As expected, the increasing in the thickness of slabs improved the stiffness of specimens with or without burning as illustrated in Fig.(13). In other words, the thinner slab have more deflections.



(a) Load-Deflection Response for Specimens with 90mm Thickness

(b) Load-Deflection Response for Specimens with 140mm Thickness

Fig.(10) Effect of Fire Flame Temperature on Load-Deflection Response of Specimens

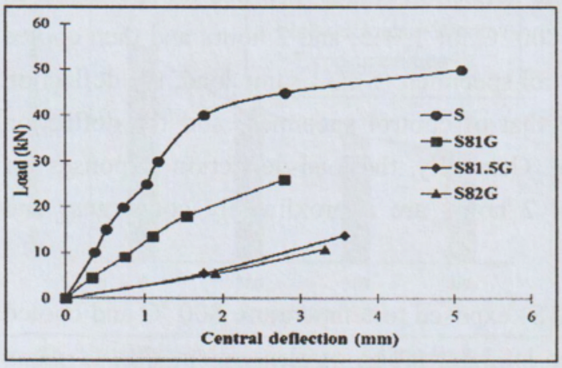


Fig.(11) Effect of Exposure Time on Load-Deflection Response of Specimens

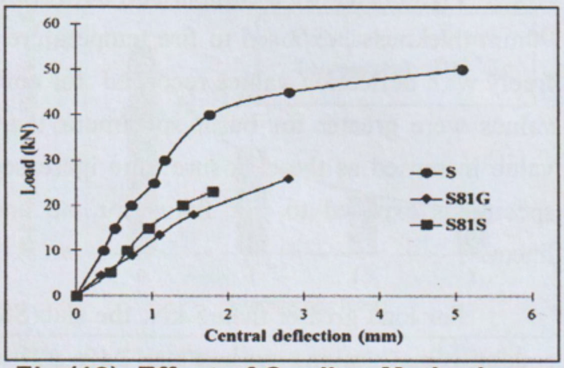


Fig.(12) Effect of Cooling Method on Load-Deflection Response of Specimens

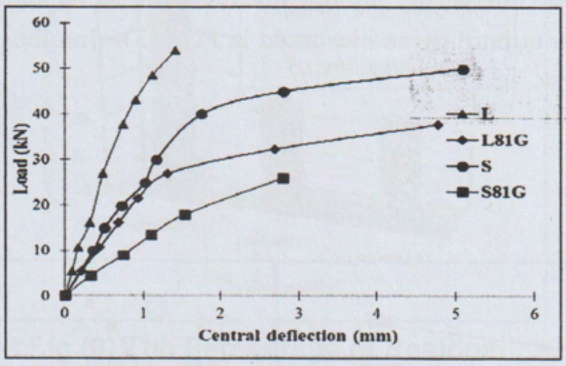


Fig.(13) Effect of Slab Thickness on Load-Deflection Response of Specimens

5. Conclusions:

In this paper, a series of experiments was performed to investigate the residual strength of reinforced concrete bubble slabs exposed to fire flame temperatures ranging from 200 to 800 °C for a burning duration between 1 hour and 2 hours. Based on the experimental results presented in this paper, the following conclusions may be drawn from this study:

1. Cracks were observed on the concrete surface of the bubble slab specimens after burning, and these cracks become deeper with more intensity as the fire flame temperature increased. The sudden cooling had a great effect on the cracks formation.
2. The shear strength of the bubble slabs dropped rapidly when the exposure temperatures exceeded 200 °C because of the reduction in the concrete compressive strength. All slabs,

exposed to fire flame temperature greater than 200 °C, failed in shear mode except for one cooled suddenly which exhibited compression failure (crushing of concrete).

3. The residual strength of the bubble slabs decreases as the exposure temperature increases. The residual strength of specimens with 90 mm thickness and exposed to fire flame for 1 hour decreased from 71.8% to 52% when the exposure temperature increased from 200 to 800 °C, respectively.

4. Prolonging the burning time decreases the residual strength of the bubble slabs. The residual strength of specimen, exposed to fire flame temperature 800 °C for 2 hours, reached to 21.6%. For same specimen exposed to fire flame for 1 hour, the residual strength was 52%.

5. Increasing the thickness of bubble slabs enhanced the residual load capacity, increasing the thickness by 56% increased the ultimate load capacity by 45% for specimen exposed to fire flame temperature 800 °C for 1 hour.

6. When the specimen was cooled suddenly, there is a decrease in the residual flexural strength percent, and central deflection percent compared with the gradual cooling. Generally, the decrease in residual strengths was 13%.

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