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Residual Punching Strength of NSC, HSC and LWC Panels Exposed to High Temperatures

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Abstract

This work aims at studying the post – heating behavior of normal strength concrete (NSC), high strength concrete (HSC) and lightweight concrete (LWC) slabs and assessing the residual punching shear strength of two-way slab specimens. Eleven reduced scale reinforced concrete slab specimens divided into three main groups, each of which is divided into subgroups for heating levels, representing the NSC, HSC and LWC types of corresponding cube compressive strengths of 50, 94 and 37 N/mm2 respectively, are prepared in the laboratory. Residual punching shear strengths, load – deflection curves, crack patterns, failure characteristics and details, and effects of temperature level exposure are all recorded, investigated and discussed. Effects of concrete type and structural failure type when slabs are exposed to different temperature levels are also discussed. Results indicate reduction of strength with exposure to high temperature. Residual punching strength percentages at maximum temperature exposure are 33.3%, 53.8% and 69.2% for NSC, HSC and LWC slabs respectively. When the temperature reaches (700 0C), the type of failure is changed from the expected punching shear failure to flexural failure in both slab specimens of NSC and HSC, but for the LWC slab specimen, the type of failure remains punching shear at this high temperature.

الخلاصة

هذا البحث يهدف إلى دراسة تصرف نماذج من البلاطات الخرسانية ذات الاتجاهين: الاعتيادية المقاومة (NSC)، العالية المقاومة (HSC) والخفيفة الوزن (LWC) وتقييم مقاومات الانثناء والقص الثاقب المتبقية فيها بعد تعريضها للحرارة.

لقد جرى تحضير اثنين وعشرين نموذج من البلاطات الخرسانية المسلحة ذات الأبعاد المصغرة في المختبر، وقد تم تقسيم هذه النماذج إلى خمس مجموعات لتمثل كل من الخرسانة الاعتيادية المقاومة (NSC)، الخرسانة العالية المقاومة (HSC) والخرسانة الخفيفة الوزن (LWC) والتي كانت مقاومات اسطواناتها للانضغاط 50، 94و 37 نت/ملم2 على التوالي.

من خلال الفحوصات والأعمال المختبرية تم تسجيل وتحري ومناقشة كل من المقاومات المتبقية للانثناء والقص الثاقب، منحنيات الحمل – الهطول، وأنماط التشقق، خصائص الفشل وتفاصيله وتأثيرات مستوى التعرض للحرارة. وكذلك تمت مناقشة تأثيرات كل من نوع الخرسانة المستعملة في البلاطات ونوع الفشل الذي تعانيه عندما تتعرض لمستويات مختلفة

من الحرارة. لقد أشرت النتائج انخفاض مقاومة النماذج بتعريضها للحرارة العالية، حيث كانت النسب المئوية لمقاومة القص الثاقب المتبقية بعد التعرض لأقصى درجة حرارة 33.3%، 53.8% و 69.2% لكل من (NSC)، (HSC) و (LWC) على التوالي، عندما تصل درجة الحرارة المسلطة الى (700 0C) يتغير نوع الفشل في البلاطات الخرسانية (NSC)و(HSC) من القص الثاقب الى الفشل بالانثناء ولكن في البلاطات الخرسانية (LWC),نوع الفشل بقي نفسه القص الثاقب في هذه الدرجة العالية من الحرارة.

1. Introduction

The exposure of structural members to high elevated temperatures will cause change in the properties of their constituents, namely concrete and steel, and in structural behavior. One type of these structural members is reinforced concrete slab.

One of the common causes of failure of flat plate structures is punching shear failure under relatively high concentrated loads.

When flat plates are subjected to high elevated temperatures, all changes in material properties and structural behavior make new differences and add new effecting factors on all formulas. Thus, it is important to improve the understanding of the punching failure mechanisms after subjecting to high temperatures to establish a more reliable method for predicting the residual punching strength in flat plate and the relationship between residual punching strength and the residual compressive strength after heating.

2. Review of Previous Works

In 1979, Lie and Leir (1), studied experimentally and theoretically the influence of the various factors affecting temperature of fire – exposed concrete slabs. The specimens were made of concrete with coarse and fine aggregates, both containing more than 99% quartz. The slabs thickness was 60, 100 and 150mm. The test was according to ASTM E119-2000a (2). They concluded that the thickness of the slab is the most important factor and the influences both of heat transfer from fire to slab and of variations in the thermal properties of concrete are relatively small.

In 1988, Shirley, Burg and Fiorato (3), studied the fire endurance of HSC slabs. They evaluated the fire performance of commercially available HSC with and without silica fume. Five test specimens ($0.9\times 0.9\times 0.102$m) were subjected to a 4–hour fire exposure following the time versus temperature relationship specified in the ASTM E119- 2000a (2) .They concluded that the fire endurance of all five specimens is not significantly different. Also, none of the five tested specimen exhibits spalling of the exposed surface nor any explosive behavior is observed.

In1996, Fahmi and Heidyat (4), investigated experimentally and analytically the behavior of reinforced concrete slabs after subjected to high temperatures and then gradually cooled.

Eighteen reinforced concrete slab specimens were fabricated and divided into six groups each of which consists of three specimens having three different steel ratios. Each group was heated to a temperature ranging from (25 to 700) ◦ C. The results showed that the residual flexural strength decreases with the increase of the temperature.

From the literature review, it is clear that very few reports are found on the effect of high temperature on the punching shear strength and related failure resulted from concentrated load in two –way reinforced concrete NSC, HSC and LWC slabs.

Residual shear strength after exposure to high temperature is recorded and discussed for NSC, HSC and LWC slabs in this study.

3. Program of the Work

During this work, the study of the behavior of slabs was based on eleven reduced scale reinforced concrete slab specimens casted in laboratory. The dimensions of all the slab specimens were (450 × 450 × 50 mm) (length × width × thickness). Three concrete types were used in this study: normal strength concrete, high strength concrete, and lightweight concrete, with compressive strengths (fcu) of (50, 93.67, 36.67 N/mm2) respectively. Steel ratio of (0.005) was used. The specimens was cast, water cured for 28 days, air dried in the laboratory for 7 days, then subjected to different high temperatures by using electric furnace for three different durations for normal and high strength concrete 1hr, 2hrs, and 4hrs, and for two different durations for light weight concrete 1hr, and 4hrs, then after 24hrs; they were tested to failure under a concentrated load through a central column of dimension 30 × 30 mm.

The slabs were simply supported along the four edges with a clear span of 420 mm in each direction, corner up lifts were prevented by placing loads at corners. Also, control specimens (150mm) cubes were tested to determine the compressive strength before and after heating for each type of concrete used at each duration of heating.

3.1 Materials

General description of the materials used in the tests is given below:

3.1.1 Cement

Ordinary Portland cement (type 1) according to ASTM C150-89(5) produced in Lebanon was used throughout this study. Results of chemical and physical analysis indicate that the available cement is conformed to the Iraqi specification (I.O.S) No.5/1984(12).

3.1.2 Fine Aggregate

Normal weight, natural sand brought from Akhaidher area, is used as fine aggregate.The grading of sand is conformed to the requirements of the Iraqi specification No.45/1984(13) zone 2.

3.1.3 Coarse Aggregates

3.1.3.1 Normal Weight Coarse Aggregate

Ten millimeter maximum size coarse aggregate was used throughout the tests of normal and high strength concretes. Gradation of the normal weight coarse aggregate is conformed to the requirements of the Iraqi specification No.45/1984(13).

3.3.3.2 Light Weight Coarse Aggregate

Local naturally occurred LWA of porcelinite stone is used as coarse aggregate throughout the tests of light weight concrete. The quarry of this stone is located in Trefawi area (Rutba) at the western desert in Anbar governorate. The lumps are firstly crushed into smaller size manually by means of a hammer in order to facilitate the insertion of the lumps through the feed opening of the crusher machine. The Jaw crusher is setup to give a finished product of about 12.5 mm maximum aggregate size. Table (1) shows the mineral analysis of porcelinite aggregate. Physical and chemical properties are determined for porcelinite coarse LWA. Tables (2) and (3) list these properties. The grading of coarse porcelinite aggregate is within the limits of ASTM C330-2003(6) as shown in Table 4.

Table (1) Mineral analysis of porcelinite aggregate*

Compounds	Opal- CT	Quartz	Calacite	Dolomite	Gypsum	Halite	Apatite	Clay
% by weight	65	10.4	6.25	7.15	0.6	0.65	1.85	7.72

*Mineral analysis is made by the State Company of Geological Survey and Mining

Table (2) Physical Properties of porcelinite aggregate*

Property	Specific gravity	Absorption %	Dry loose unit weight, kg/m^3	Aggregate crushing value %
Results	1.45	34	850	16

Table (3) Chemical analysis of porcelinite aggregate*

Oxides	SiO_2	CaO	MgO	SO_3	Fe_2O_3	Al_2O_3	TiO_2	CL	Loss of Ignition
%by weight	74.7	12.04	0.56	0.3	0.39	0.63	0.05	0.07	5

Table (4) Grading of light weight coarse aggregate (Porcelinite)*

Sieve Size (mm)	12.5	9.5	4.75	2.36	1.18
Passing %	100	95	10	10	5
ASTMc 330 Limits	100	80-100	5-40	0-20	0-10

*****Physical and chemical analysis are made by the State Company of Geological Survey and Mining

3.1.4 Water

Tap water was used throughout this work for both mixing and curing of concrete.

3.1.5 Steel Reinforcement

Plain wires 6 mm in diameter were used as flexural reinforcement placed in the tension face of the slab. The yield strength was determined from tensile test at the Structural Lab. of the College of Engineering / AL-Mustansiryia University, and the average yield strength was 382 N/mm2. The wires were cut to the desired length, and 90-degree hook is formed at the ends of each bar dimensioned according to sections 7.1 and 7.2 of the ACI 318/2002 Building code (7). The wires were uniformly spaced and placed in two directions at 150 mm c/c spacing each way to obtain the desired steel ratios of (0.005) respectively. Meshes consisting of 3 wires in each direction for steel ratio 0.005 have been used. A clear cover of 15 mm was provided for the mesh.

3.1.6 Superplasticizer

The superplasticizer used in this study is Glenium 51, which is free from chlorides and complies with ASTM C 494 Types A and F. Glenium 51 is compatible with all Portland cements that meet recognized international standards.

3.2 Mix Design and Proportions

3.2.1 Normal Strength Concrete Mix

Group N consists of normal strength concrete slabs. Control mix proportions of 1 (cement): 1.5 (sand): 3(gravel), and water /cement ratio of 0.45 (all by weight) were used. The above mix gave average concrete cube strength of 50 N/mm2 at 28 days, and has 68 mm slump.

3.2.2 High Strength Concrete Mix

Group H consists of high strength concrete slabs. Control mix proportions of 1 (cement): 1.134 (sand): 1.93 (gravel), and water / cement ratio of 0.264, and superplasticizer content of 1.5 % by weight of cement were used. This mix gave average concrete cube strength of 93.67 N/mm2 at 28 days, and has 56 mm slump.

3.2.3 Light Weight Concrete Mix

Group L consists of light weight concrete slabs. The aim was to produce structural LWAC according to class I of the RILEM classification which is adopted by the CEB- FIP manual (8). According to this classification, concrete should have an oven – dry density lower than (2000 kg/m3) and a compressive strength greater than 15 N/mm2. Consequently, concrete mixtures are designed in such a manner so as to satisfy these requirements. Finally, the control mix proportions of 1 (cement): 0.72 (sand): 0.91 (porcelinite), and water/ cement ratio of 0.3 and superplasticizer content of 1.2% (all by weight) were used. This mix gave average concrete cube strength of 36.67 N/mm2 at 28 days, and has 42 mm slump.

Mix proportions and details for all mixes are shown in Table (5).

Table (5) Details of mixes used in slabs

Slab group	Cement content (kg/m^3)	Aggregate content		Porcelinite content (kg/m^3)	Water content (kg/m^3)	s.p% by weight of cement	w/c ratio	Slump (mm)	Average cube compressive strength (N/mm^2)	Density of concrete (kg/m^3)
		Sand (kg/m^3)	Gravel (kg/m^3)							
N	410	615	1230	-	184.5	-	0.45	68	50	2360
H	560	635	1085	-	148	1.5	0.264	56	93.67	2432
L	550	400	-	500	150	1.2	0.3	42	36.67	1808

3.3 Heating and Cooling of Specimens

An electric furnace was used to heat the specimens (slabs and cubes), its temperature capacity is 1200 0C, see Figure (1). The furnace temperature was controlled by an electronic thermostat controller. The temperatures were continuously recorded by two thermometers positioned at the mid height side and mid top of the furnace. The recorded temperature- time curve is shown in Figure (2).

Preliminary experimental work was carried out to decide the temperatures range and duration of heating. For the cooling regime, the furnace was switched off at the end of the exposure time and the specimens were allowed to cool in the half open furnace for twenty four hours, then they were removed to cool in air for twenty four hours and then tested.

Figure (1) The Furnace used.

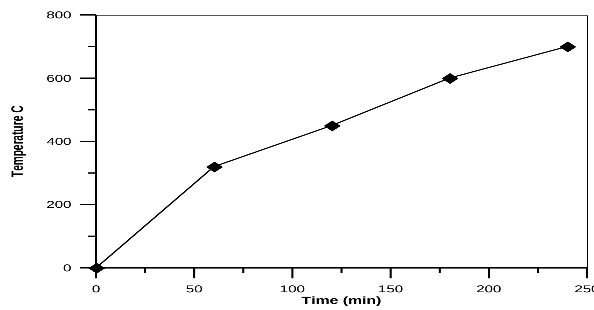

Figure (2) The temperature – time relation for the oven.

3.4 Durations of Heating and Range of Temperatures

The applied durations of heating were 1hr, 2hrs, and 4hrs for groups N and H, and 1hr, and 4hrs for group L. These durations were different in maximum temperature according to temperature – time curve of furnace, Figure (2). According to that Figure the durations of heating of 1hr, 2hr and 4hr represent the heating from (0 to 320 0C, 450 0C, and 700 0C) respectively. For groups N and H, each two slab specimens and three cubes (150 mm) were subjected to heating durations 1hr, 2hrs and 4hrs. For group L, each two slab specimens and three cubes (150 mm) were subjected to heating durations 1hr and 4hrs. The other two slab specimens and three cubes (150 mm) from each group were tested without subjecting to heating in order to notice the effect of high temperatures on the behavior of slab specimens and their compressive strength.

3.5 Compressive Strength Test

The compressive strength test was carried out according to BS 1881: part 116: 1983(9), for all (150 mm) cubes. Three cubes from each group were used to determine the compressive strength for each one and three cubes from each group at each duration of heating were used to determine the compressive strength of each heat slab specimen.

3.6 Test Machine

The machine used in this work is one of the hydraulic types available in the Structural Laboratory in Civil Engineering Dept. College of Engineering, AL-Mustansirya University, as shown in Figure (3).

Figure (3) Set – up of Test Machine

The machine which was used for compression tests of cubes was an (MFL) "300" ton capacity hydraulic universal testing machine.
Figure (4) shows the loading arrangement used through the tests.

Figure (4) Loading arrangement

4. Experimental Tests and Results

4.1 Description of Experimental Program

As mentioned previously, the test slab specimens are divided into three groups according to concrete type, and then they are divided according to the heating level. These groups are described below:

Group (N): Four NSC slab specimens having compressive strength (f_{cu}) of (50 N/mm^2).

Group (H): Four HSC slab specimens having compressive strength (f_{cu}) of (93.67 N/mm^2).

Group (L): Three LWC slab specimens having compressive strength (f_{cu}) of (36.67 N/mm^2).

Then, the groups above are divided into:

Group (N1): Four slab specimens from (N), having steel ratio (0.005) and designed to fail in punching.

Group (H1): Four slab specimens from (H), having steel ratio (0.005) and designed to fail in punching.

Group (L1): Three slab specimens from (L), having steel ratio (0.005) and designed to fail in punching.

Finally, all groups are divided according to heating into:

- (N1C), (H1C), and (L1C), slab specimens are kept in room temperature without heating.
- (N11), (H11), and (L11) slab specimens are heated for (1hr.) from (0°C to 320°C).
- (N12), and (H12) slab specimens are heated for (2hrs.) from (0°C to 400°C).
- (N14), (H14), and (L14) slab specimens are heated for (4hrs.) from (0°C to 700°C).

4.2 Ultimate Load Carrying Capacity and Residual Punching Strength for Slab Exposed to High Temperatures

The slab specimens reinforced with steel ratio of (0.005) are designed to fail in punching shear for all three types of concrete (NSC, HSC and LWC). The test results of the ultimate load of the reference slab specimens and those exposed to high temperatures are shown in Tables (6), (7) and (8) for groups N1, H1 and L1 respectively. It is clear from the test results that, the values of ultimate load capacity are related to compressive strengths, which decrease when exposed to high temperatures except for NSC at (320 ° C) which increases and the ultimate load capacity for slab N11 is increased by (16.67%) over the original load.

From the test results shown in Tables (6), (7), (8) and (9) regarding ultimate load capacity, it is obvious that the effect of high temperature on the ultimate load capacity of slabs varies over the various types of concrete panels. At (320 ° C), the ultimate load capacity for panel N11 increases by (16.67%) over original load. However, for ultimate load capacity of panels N12 and N14, a decrease of (38.89% and 66.67%) from original load is recorded respectively.

Table (6) Test results of slab specimens of group (N1)

Specimen	Temperature C ° Stage	Compressive Strength (N/mm²)	Residual Ultimate Load (kN)	Residual Load (%)	Maximum Deflection (mm)	Failure Mode
N1C	Room Temp	50	18	100	2.77	Punching
N11	320	52.1	21	116.67	5.45	Punching
N12	450	36.52	11	61.11	2.82	Punching
N14	700	25.2	6	33.33	7.23	Flexural

Table (7) Test results of slab specimens of group (H1)

Specimen	Temperature C ° Stage	Compressive Strength (N/mm²)	Residual Ultimate Load (kN)	Residual Load (%)	Maximum Deflection (mm)	Failure Mode
H1C	Room Temp	93.67	26	100	7.74	Punching
H11	320	91.83	24.5	94.23	11.72	Punching
H12	450	62.63	18	69.23	4.91	Punching
H14	700	36.2	14	53.84	2	Flexural

Table (8) Test result of slab specimens of group (L1)

Specimen	Temperature C ° Stage	Compressive Strength (N/mm²)	Residual Ultimate Load (kN)	Residual Load (%)	Maximum Deflection (mm)	Failure Mode
L1C	Room Temp	36.67	13	100	3.66	Punching
L11	320	31	11	84.61	3.58	Punching
L14	700	23.2	9	69.23	6.39	Punching

For HSC at (320° C), the ultimate load capacity for H11 decreases by (5.77%) from original load, but, for (450° C and 700° C) heating the ultimate load capacity for panels H12 and H14 decreases by (30.77% and 46.16%) from original load respectively.

For LWC at (320° C), the ultimate load capacity for panel L11 decreases by (15.39%) from original load, and at (700° C), the ultimate load capacity for panel L14 decreases by (30.77%) from the original load. The ratios of the ultimate load for the slabs (H1) to slabs (N1) under (room temperature, 320° C, 450° C and 700° C) are (1.44, 1.16, 1.63 and 2.33) respectively, see Table (9), where these ratios increase slightly with the increases of temperature except at (320° C) where this ratio is less than that at (room temperature). This indicates that the use of HSC has an obvious effect on the increase of slab punching resistance to high temperatures greater than the NSC with the same steel ratio in spite of the sensitivity of HSC to high temperature from the material point of view. Table (9) shows the ratio of ultimate load of the slabs (H1) to slabs (L1) at (room temperature, 320° C, and 700° C) where the ratios are (2, 2.22 and 1.55) respectively. It is shown that the ratios of the ultimate load of group (H1) to ultimate load of group (N1) are less than the ratios of group (H1) to (L1) at (room temperature and 320° C), but more than it at (700° C). All these ratios show that the use of HSC increases the ultimate load capacity more than LWC at high temperatures, but these ratios decrease after (320° C), which indicates that the use of LWC has an obvious effect on the increase of slab resistance to high temperature at temperatures up to (700 ° C), and means that the LWC is better protective material to the steel reinforcement more than NSC which becomes as a buff after this temperature. The ratios of ultimate load for the slabs (L1) to slabs (N1) are shown in Table (9) at (room temperature, 320° C, and 700° C) are (0.722, 0.523 and 1.5) respectively. These ratios show that the effect of using LWC appears significant at (700° C) which is clearly more than the NSC capacity, however; it is not with temperatures below (700° C). The increase of the ultimate load of slab of group (L1) at (700° C) in spite of the low compressive strength compared with slab of group (N1), shows the benefit of using LWC at higher temperatures (≅ 700° C).

Figure (5) shows the percentages of the residual load capacity of slabs versus temperature for groups N1, H1 and L1.

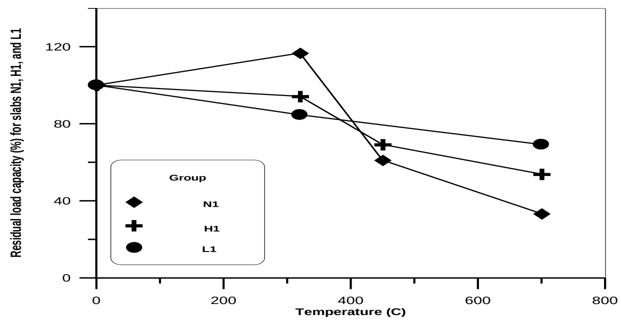

Figure (5) Effect of high temperature on the residual load capacity for the punching groups of slab specimens

Table (9) Ultimate punching load and deflection of various NSC, HSC, and LWC panels under high temperatures

Temp. Stage C°	Slab Specimen 1		Ultimate Load (kN)	Max. Deflection (mm)	Slab Specimen 2		Ultimate Load (kN)	Max. Deflection (mm)	Ratio of max. values of slab specimen 1 to 2	
	No.	Type			No.	Type			Ultimate Load	Max. Deflection (mm)
Room. Temp.	H1C	H1	26	7.74	N1C	N1	18	2.77	1.44	2.8
320	H11	H1	24.5	11.72	N11	N1	21	5.45	1.166	2.15
450	H12	H1	18	4.91	N12	N1	11	2.82	1.63	1.74
700	H14	H1	14	2	N14	N1	6	7.23	2.33	0.276
Room Temp.	H1C	H1	26	7.74	L1C	L1	13	3.66	2	2.11
320	H11	H1	24.5	11.72	L11	L1	11	3.58	2.22	3.27
450	H12	H1	18	4.91	_	_	_	_	_	_
700	H14	H1	14	2	L14	L1	9	6.39	1.55	0.313
Room Temp.	L1C	L1	13	3.66	N1C	N1	18	2.77	0.722	1.32
320	L11	L1	11	3.58	N11	N1	21	5.45	0.523	0.656
700	L14	L1	9	6.39	N14	N1	6	7.23	1.5	0.883

4.3 Load – Deflection Relationship

The load – deflection relationships of punching slab specimens, with steel ratio (0.005), for NSC,HSC and LWC slab specimens ,i.e., groups N1, H1, and L1 respectively are presented in Figures (6), (7) , (8) and (9) at (room temperature, 320° C, 450° C and 700° C) respectively.

With reference to the above curves, it can be seen that the load-deflection curves at (room temperature) exhibit three stages each with different slope.

The first stage is the elastic or uncracked stage, the second stage is multiple cracking stage; and the third is the plastic stage, which represents the yielding of reinforcement and widening of cracks.

These three stages are obviously shown for the (room temperature) condition, Figure (6), for slab specimens of groups N1, H1 and L1.

At temperature (320° C), the three above stages are also pronounced see Figure (7), especially for slab specimens N11 and H11. For slab specimen L11, the behavior is kept similar but more softened.

At temperature (450° C), these stages are less pronounced especially for slab specimen N12, while for slab specimen H12 the three stages are still pronounced but less than that at temperature (320° C), as shown in Figure (8).

At temperature (700° C), the load-deflection relations of slab specimens are flatter, representing softer load-deflection behavior than that of slab specimens at (room temperature) and the behavior of slab specimen N14 shows this more than slab specimen L14, but, the behavior of the slab specimen H14 shows brittle behavior. This can be attributed to both the reduction of modulus of elasticity of concrete and the moment of inertia due to the increase in the amount of cracks (rigidity reduction). So, this leads to the fact that the formation of cracks in LWC at high temperature is less than that at NSC, and the cracks formation in HSC at high temperature is less than that at NSC and LWC. These facts are observed on the slab specimens in this work.

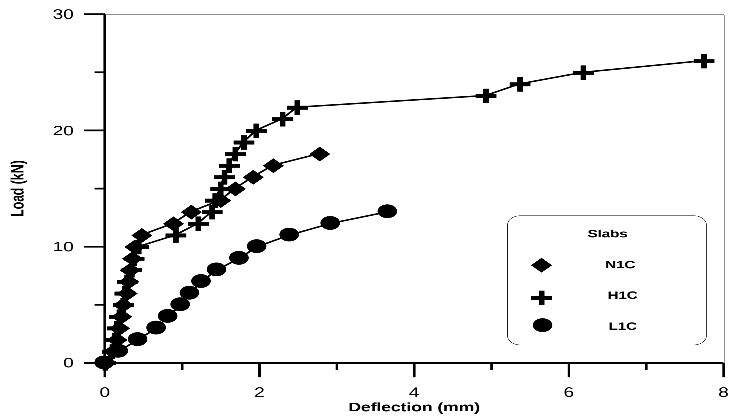

Figure (6) Load –Deflection relationship for punching slab specimens N1C, H1C and L1C (room temperature conditions).

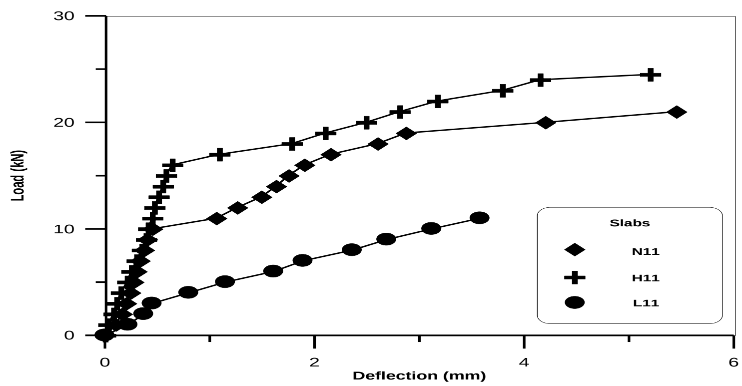

Figure (7) Load-Deflection relationships for punching slab specimens N11, H11 and L11 (320C.)

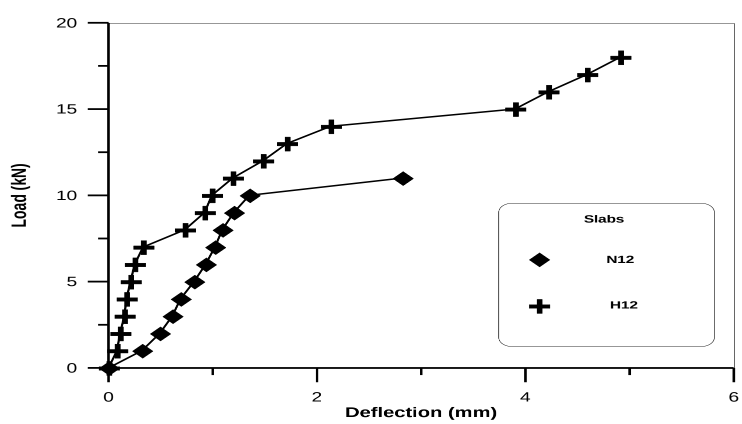

Figure (8) Load –deflection relationships for punching slab specimens N12 and H12 (450° C).

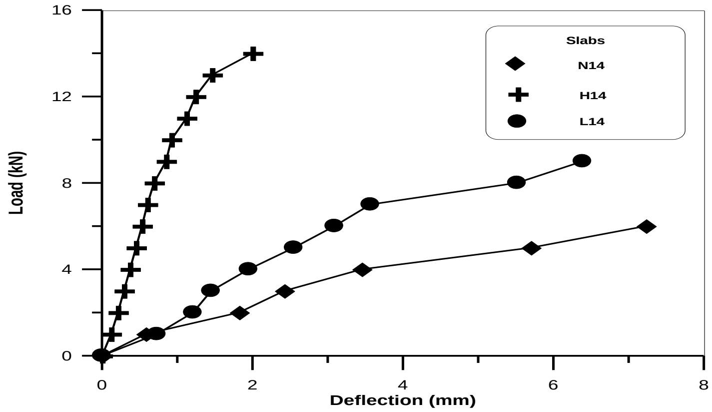

Figure (9) Load –deflection relationships for punching slab specimens N14, H14 and L14 (700° C).

The load – deflection relationships with different levels of temperature for the same concrete type slab specimens are presented in Figures (10) to (12). It can be seen that the deflection increases with the increase in the heating temperature. This can be attributed to the fact that heating causes a reduction in slab stiffness which is essentially due to the reduction in the modulus of elasticity of concrete. These results are on line with Harada [10] and Umran [11] results.

The load – deflection relationships for the slab specimens of group N1 are shown in Figure (10). The increase in temperature causes the flattening of curves, and this is more pronounced for LWC slab specimens of group L1, as shown in Figure (12). However, for HSC slab specimens of group H1, the curves shape of slab specimens at the (room temp., 320° C, 450° C and 700° C) is different for each temperature. The slab specimens' behavior in general becomes more brittle, with reduction in both ultimate load and maximum deflection as the temperature increases. However, HSC slabs maximum deflection at the temperatures (room temp., 320° C and 450° C) is higher than that of NSC slabs, but the maximum deflection decreases at temperature (700° C), as compared with NSC. Also, when compared with LWC at the temperatures (room temp., 320° C), the maximum deflection increases, but, the value of the maximum deflection decreases for HSC slabs at temperature (700° C).

For LWC slabs, the value of the maximum deflection increases at (room temperature), and then the value decreases at the temperatures (320° C and 700° C), as compared with NSC, see Table (9).

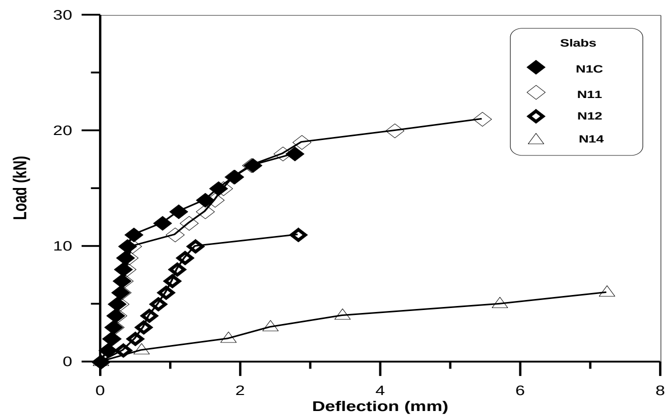

Figure (10) Load –Deflection relationship for NSC punching slab specimens at different temperature levels.

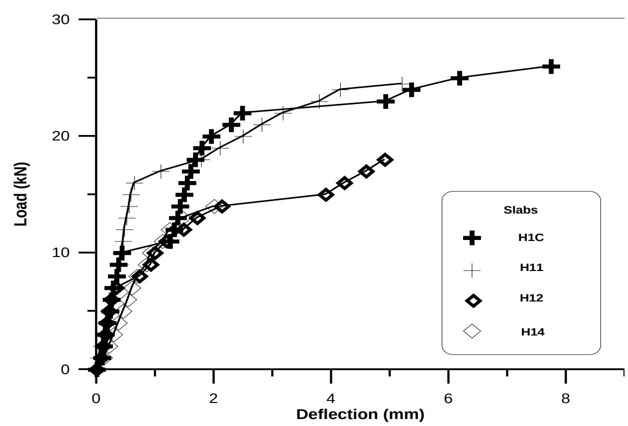

Figure (11) Load–Deflection relationship for HSC punching slab specimens at different temperature levels.

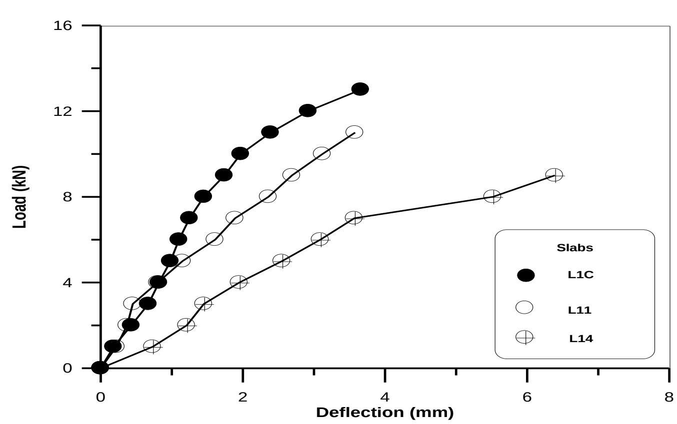

Figure (12) Load –Deflection relationship for LWC punching slab specimens at different temperature levels.

4.4 Crack Pattern

When the load is applied to the reinforced concrete (punching) slab specimens, with steel ratio (0.005), except N14 and H14, the first crack forms in the tension surface of the slab specimens under the loaded area when the load reaches various percentages of the ultimate load depending on the temperature level.

As the load is increased, radial cracks in the tension surface start to appear and extend from a perimeter below the loaded area towards the slab specimen edges. At the same time, the cracks increase in number at the central region of the slab specimen. Cracking at the supports of the panels is also noticed at this stage. This crack pattern appears faster at the tested slab specimens which are exposed to heating and occurs faster as temperature increases .A complete punching shear failure occurs by increasing the load. Figure (13) shows the tested slab specimens and their cracking patterns. Flexural failure is observed for HSC and NSC panels at max. temperature (700 ° C).Yield lines are formed at failure.

4.5 Shape and Size of the Punching Failure Zone

It is observed that the shape of the punching failure zone in plan ranges from a circle to a square with round corners. The shapes can be modeled similar to that recommended by the ACI 318 / 2002 [(7)]. Figure (13) shows the shapes of failure zones of the tested slabs. The areas of the punching failure zones and their perimeters are measured by using AutoCAD program.

The measured areas and perimeters are shown in Table (10). It can be noted that the size of the punching failure zone for the heated slab specimens is larger in general than that for specimens not exposed to heating especially for the slab specimens heated to (320 ° C).

The decreasing percentage in area for slab specimen N11 is 17.44% from the area of N1C, and the increasing percentages in area for the slab specimens H11 and L11 are 115.6% and 146.6% over the area of H1C and L1C respectively.

For the slab specimens N12 and H12 (450 ° C), the size of the punching failure zones is larger than that for the slab specimens N1C and H1C by 23.78% and 30.75% respectively .On the other hand, and for the slab specimen L14 the increasing percentage is 22.9% more than that for L1C , these percentages are smaller than those for H11 and L11.This leads to the conclusion that an increase in the size of the punching failure occurs at the first level of heating then this zone size decreases with temperature rise. However, in general, this size remains greater than that of specimens under (room temperature).It must be noted that this area includes the spalled portion outside the shear crack.

4.6 Punching Shear Failure Angle

The punching failure angles of the punching pyramid are measured by indicating the dimensions of crushed zone at the center line passing through the loaded area.

At (room temperature), it is observed that the angle of the punching failure is the greatest for HSC slabs and the smallest for LWC slabs.

However, for specimens exposed to various temperature levels, the angles vary for various slab types; showing a decrease in general compared to those of (room temperature) condition, although an increase is recorded at higher temperatures, except for NSC slabs.

For the LWC slab specimen L11 , the failure pyramid that is pushed out in slab specimen has a much wider base than that in slab specimens with less compressive strength when exposed to high temperatures ,see Table (10) ,in which the angles are measured with respect to the horizontal line, see Figure (14).

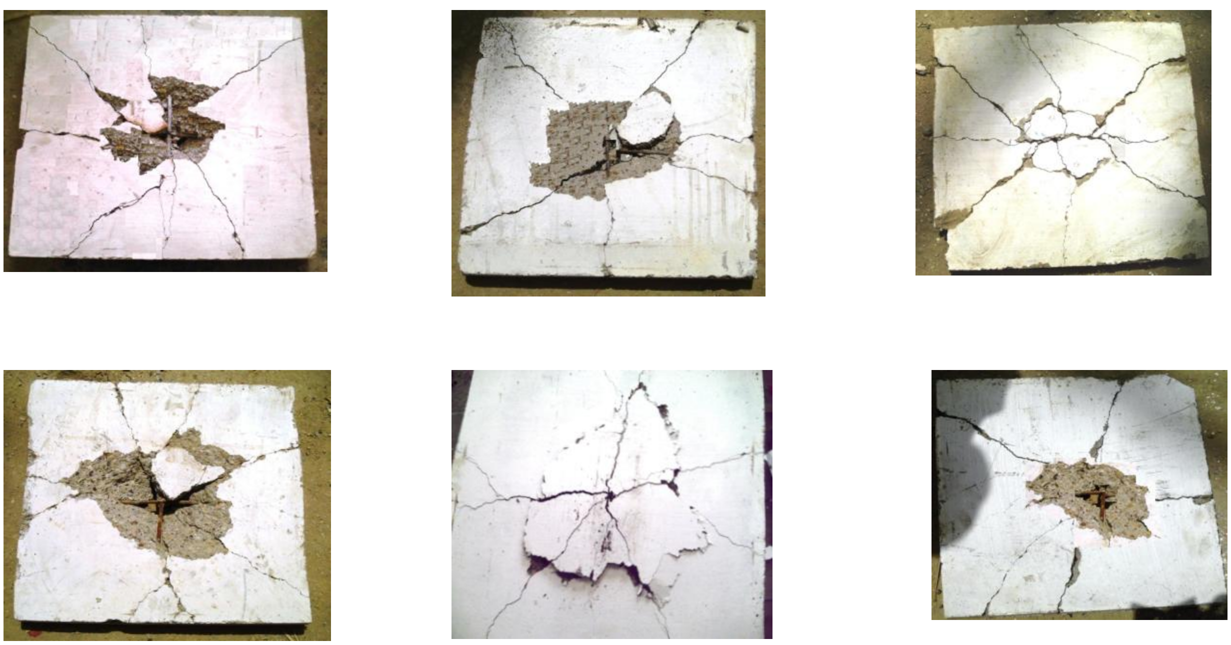

Figure (13) Some of slab specimens of groups N1, H1 and L1

Table (10) Details of the measured failure area in slab specimens failed in punching.

Group	Specimen Identification (exposure degree)	Measured Area (mm^2)	Measured Perimeter (mm)	Failure Angle (degree)
N1(NSC)	N1C (Room temperature)	32566	843	31.2
	N11(320 °C)	26884	697	34
	N12(450 °C)	40313	923	27.75
H1 (HSC)	H1C (Room temperature)	28402	825	33
	H11(320 °C)	61250	1064	22
	H12(450 °C)	37136	890	29
L1 (LWC)	L1C (Room temperature)	34416	987	30.46
	L11 (320 °C)	84880	1138.27	18.43
	L14 (700 °C)	42297	1056	26.56

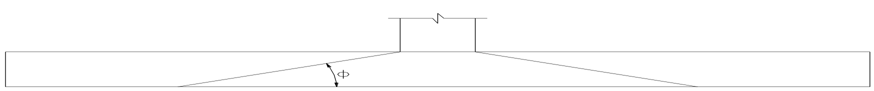

Figure (14) Punching shear failure angle.

5. Conclusions

Depending on the results of this study, the following conclusions can be drawn

1. Concrete compressive strengths for NSC, HSC and LWC reduce after exposure to high temperature (except NSC at 320 0C where a little increase of about (4.2%) takes place). The reduction percentages are :
   - The percentage reductions in compressive strength for NSC after exposure to (450 ^{0}C and 700 ^{0}C) are about (26.96% and 49.6%) from original strength respectively.
   - The percentage reductions in compressive strength for HSC after exposure to (320 ^{0}C, 450 ^{0}C and 700 ^{0}C) are about (1.97 %, 33.14 % and 61.36 %) from original strength respectively.

- The percentage reductions in compressive strength for LWC after exposure to (320 ^{0}C and 700 ^{0}C) are about (15.47 % and 36.74 %).

2. When the temperature reaches (700 ^{0}C), the type of failure is changed from the expected punching shear failure to flexural failure in both slab specimens of NSC and HSC, but for the LWC slab specimen, the type of failure remains punching shear at this high temperature. This may refer to the fact that the materials properties (steel bars and concrete) less deteriorate for LWC slabs exposed to high temperatures compared to NSC and HSC slabs.
3. The ultimate load capacity for slab specimens decreases significantly when subjected to high temperatures (except for the slab specimen N11 (320$^{\circ}C$) as they exhibit increase of (16.67 %) from original load respectively). The percentages of reduction depend mainly on the temperature level, and concrete type, as follows :
   - The percentage reductions in ultimate load capacity for NSC slab specimens designed to fail in punching after exposure to (450 ^{0}C and 700 ^{0}C) are about (38.89 % and 66.67 %) from the original load respectively. For HSC slab specimens designed to fail in punching after exposure to (320 ^{0}C, 450 ^{0}C and 700 ^{0}C), the reductions are about (5.77 %, 30.77 % and 46.16 %) from the original load respectively. For LWC slab specimens designed to fail in punching after exposure to (320 ^{0}C and 700 ^{0}C), the reductions are about (15.89 % and 30.77 %) from the original load respectively.
4. The load – deflection relationships are affected by the type of concrete slab, and the temperature level :
   - The effect of concrete type is obvious at (room temperature) and other temperature levels. The behavior of HSC slab specimens is more brittle than the NSC and LWC slab specimens, and the behavior of LWC slab specimens is the flattest at all temperature levels.
   - The load – deflection relationships become softener in general as the temperature increases for NSC, HSC and LWC slab specimens.
   - The load – deflection relationships for the punching slab specimens, of steel ratio (0.005), exhibit three stages each with different slope.
5. The size of the punching shear failure zones for the heated slab specimens is found larger than that for specimens not exposed to heating.
6. The punching pyramid failure angle increases as the slab strength increases, where the smallest values are for LWC slab specimens and the highest values are for HSC slab specimens, in general.

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