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Residual Flexural 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 flexural strength of two-way slab specimens.

Eleven reduced scale reinforced concrete slab specimens divided into three main groups representing the NSC, HSC and LWC types of corresponding cube compressive strengths of 50, 94 and 37 N/mm^2 respectively, are prepared in the laboratory.

Residual flexural strength, 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 when slabs are exposed to different temperature levels are also discussed.

Results indicate reduction of strength with exposure to high temperature. Residual flexural strength percentages at maximum temperature exposure (700°C) are 44.5%, 38.7% and 45.5% for NSC, HSC and LWC slabs respectively.

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

من خلال الفحوصات والأعمال المختبرية تم تسجيل وتحري ومناقشة كل من المقاومات المتبقية للانثناء، منحنيات الحمل – الهطول، وأنماط التشقق، خصائص الفشل وتفاصيله وتأثيرات مستوى التعرض للحرارة. وكذلك تمت مناقشة تأثيرات كل من نوع الخرسانة المستعملة في البلاطات عندما تتعرض لمستويات مختلفة من الحرارة. لقد أشرت النتائج انخفاض مقاومة

النماذج بتعريضها للحرارة العالية، حيث كانت النسب المئوية لمقاومة الانثناء المتبقية بعد التعرض لأقصى درجة حرارة 44.5%، 38.7% و 45.5% لكل من (NSC)، (HSC) و (LWC) على التوالي.

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.

The ultimate flexural strength of reinforced concrete slabs supported under comparatively simple conditions can be estimated with one or more from the analysis methods like the yield line theory suggested by K.W. Johansen. (1)

Many studies on flexural strength in two way slabs have been made, but few studies were made on residual flexural strength in two way slabs after exposing to high temperatures. Some of these studies focused on the slabs subjected to uniform load with different cases' of supporting.

This study is intended to predict the behavior of two way slabs under concentrated load after heating to different temperatures, to find the effect of heating on the residual flexural strength, and the relationship between residual flexural strength and the residual compressive strength after heating.

2. Review of previous works

In 1979, Lie and Leir (2), 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 thicknesses were 6, 10 and 15cm. The test was according to ASTM E119-2000a (11). 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× 0.9× 0.102m) were subjected to a 4–hour fire exposure following the time versus temperature relationship specified in the ASTM E119-2000a (11) .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. Some cracks were formed over embedded reinforcement during the fire tests; however, those cracks appeared in both the nonsilica and silica fume concrete specimens.

In1996, Fahmi and Heidyat (4), investigated experimentally and analytically the behavior of reinforced concrete slabs (600 × 600 × 40mm) 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 at 500˚C 12% from the original strength and at 700˚C 35% from the original strength for steel ratio (0.00492). Also, the thermal and structural analysis results were in good agreement with the experimental results.

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), the dimensions selected according to the test machine dimensions and the furnace used. Three concrete types were used in this study: normal strength concrete, high strength concrete, and lightweight concrete, with compressive strengths (f_{cu}) of (50, 93.67, 36.67 N/mm^2) respectively. Steel ratio of (0.002) was used. The specimens were 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.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(12) 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(5)

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(6) 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 testes of normal and high strength concretes. Grading of the normal weight coarse aggregate is conformed to the requirements of the Iraqi specification No.45/1984(6).

3.1.3.2 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(7).

Table (1) Mineral analysis of porcelinite aggregate*

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

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

Table (2) Physical Properties of porcelinite aggregate*

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

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

Table (3) Grading of light weight coarse aggregate (Porcelinite)*

Sieve Size(mm)	*Passing%*	*ASTMc330 Limits.*
12.5	*100*	*100*
9.5	*95*	*80-100*
4.75	*10*	*5-40*
2.36	*10*	*0-20*
1.18	*5*	*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-Mustansirya University, and the average yield strength was 382 N/mm^2. 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 (8). The wires were uniformly spaced and placed in two directions at 150 mm c/c and 300 mm c/c spacing each way to obtain the desired steel ratios of (0.005 and 0.002) respectively. Meshes consisting of 2 wires in each direction for steel ratio 0.002 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/mm^2 at 28 days, and has 68 mm slump (from three mixes).

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/mm^2 at 28 days, and has 56 mm slump (from three mixes).

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 (52). According to this classification, concrete should have an oven –dry density lower than (2000 kg/m^3) and a compressive strength greater than 15 N/mm^2. 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/mm^2 at 28 days, and has 42 mm slump (from three mixes).

Mix proportions and details for all mixes are shown in Table (4).

Table (4) 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 shown in Figure (1) used to heat the specimens (slabs and cubes). Its temperature capacity is 1200 ^{0}C. 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 after which were removed to cool in air for twenty four hours and then tested.

Figure (1) The Furnace used

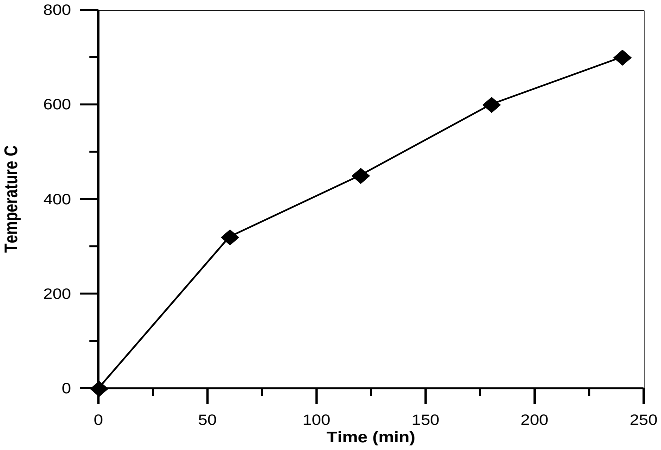

Figure (2) The temperature –time relation for the oven.

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 ^{0}C, 450 ^{0}C, and 700 ^{0}C) respectively, notice that the (room temp. =25˚C) .For groups N and H, each two slab specimens with different steel ratio and three cubes (150 mm) were subjected to heating durations 1hr, 2hrs and 4hrs. For group L, each two slab specimens with different steel ratio and three cubes (150 mm) were subjected to heating durations 1hr and 4hrs. The other two slab specimens with different steel ratio 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(54), 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 heating 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

3.7 Description of Experimental Program

As mentioned previously, the test slab specimens are divided into three groups according to concrete type, and then they are subdivided according to the heating level. These groups are described in Table (4).

3.8 Flexural Slab Specimens

The load –deflection relationship of flexural slab specimens, with steel ratio (0.002), for NSC,HSC and LWC slab specimens of groups N2,H2 and L2 respectively are presented in Figures (5),(6),(7) and (8) at (Room temp. ,320 ° C,450 ° C and 700 ° C) respectively.

At (room temperature), Figure (5) shows that the behavior of the slab specimen H2C is essentially linear up to yield. For NSC and LWC slabs, a clear change of slope is observed at points indicating yielding and that cracks take place; before that, the three slab specimens N2C, H2C and L2C are seen as having similar (elastic) behavior.

At temperature 320 ° C, similar behavior is noticed for slab specimens N21, H21 and L21 except considering the variation in the ultimate load capacity, see Figure (6).

At temperature (450 ° C), Figure (7) shows that the behavior of the slab specimens N22 and H22 is similar up to approximately the same yield point and then the deflection of the slab specimen H22 continues to increase with the load in a “flat “ manner more than that of the slab specimen N22 which “ceases” quickly. This leads to the conclusion that the behavior of the HSC panels differs with the variation of the temperature level, and shows better performance than other panel types.

At temperature (700° C), Figure (8) shows that the load – deflection relations of slab specimens are softener in general compared with those of lower temperatures. The deflection increases rapidly for the slab specimen N24 more than that in slab specimens L24 and H24 which leads to the fact that the NSC slabs deterioration at high temperature is more pronounced than LWC ones. However, the behavior of the HSC slabs remains the best in spite of its sensitivity to high temperature, as recorded for compressive strength tests.

Table (5) Slab Specimens Classification

Major Group	*Compressive Strength (f_{cu}) N/mm²*	*Minor Group*	*Steel Ratio*	*Design Failure Type*	*Slab Specimen*	*Temperature Stage ˚C*
N (NSC)	*50*	*N2*	*0.002*	*Flexural*	*N2C*	*Room Temp.*
					N21	*320*
					N22	*450*
					N24	*700*
H (HSC)	*93.67*	*H2*	*0.002*	*Flexural*	*H2C*	*Room Temp.*
					H21	*320*
					H22	*450*
					H24	*700*
L (LWC)	*36.67*	*L2*	*0.002*	*Flexural*	*L2C*	*Room Temp.*
					L21	*320*
					L24	*700*

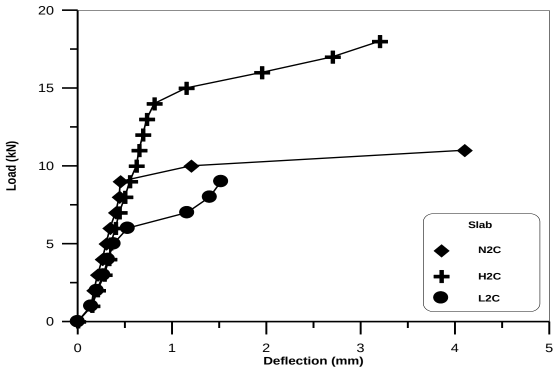

Figure (5) Load –deflection relationships for NSC, HSC and LWC flexural slab specimens (room Temperature).

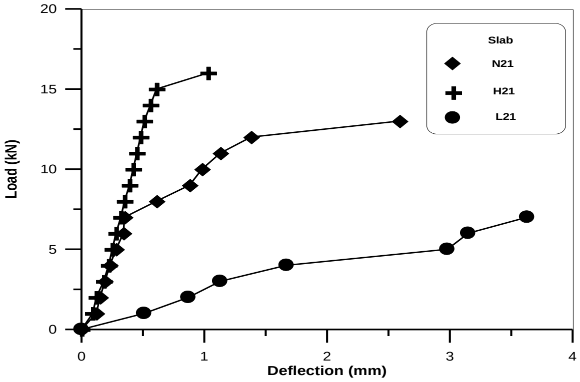

Figure (6) Load –deflection relationships for NSC, HSC and LWC flexural slab specimens (320° C).

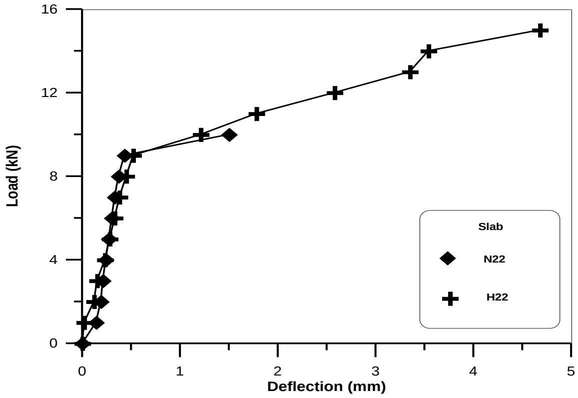

Figure (7) Load –deflection relationships for NSC and HSC flexural slab specimens (450° C).

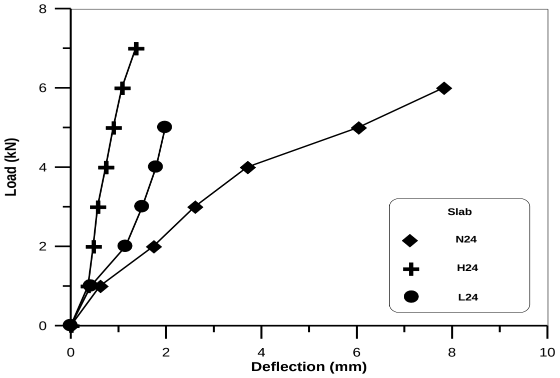

Figure (8) Load –deflection relationship for NSC, HSC and LWC flexural slab specimens (700° C).

Figures (9) ,(10) and (11) show the variations in behavior among slab specimens for the same concrete type with different levels of temperature .Figure (9) shows the NSC slab specimens of group N2 with different levels of temperature . This Figure shows that the deflection increases as temperature increases and the slabs become more softened with the increase of temperature except at (320° C) which shows an increase in the ultimate load and a decrease in the deflection more than that at (room temperature).

Figure (10) shows the HSC slab specimens of group H2 with different levels of temperature. This Figure shows that the slab specimen behaviors are similar in general to NSC slabs but less softened. Figure (11) shows the LWC slab specimens of group L2 with different levels of temperature. This Figure shows that the behavior of the slab specimens of group L2 exhibits variation in load capacity and clear increase in the deflection with temperature at all stages of loading except for L24 at the ultimate load.

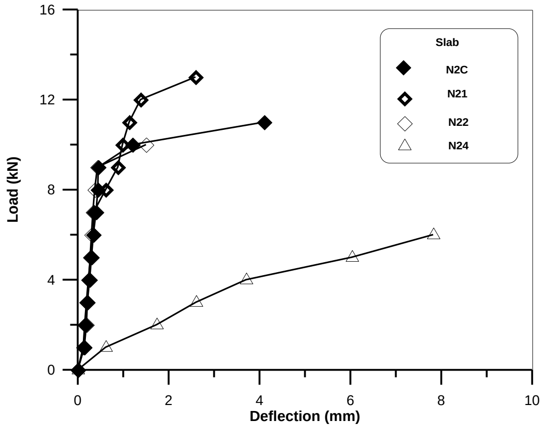

Figure (9) Load –Deflection relationship for flexural NSC slab specimens at different temperature levels.

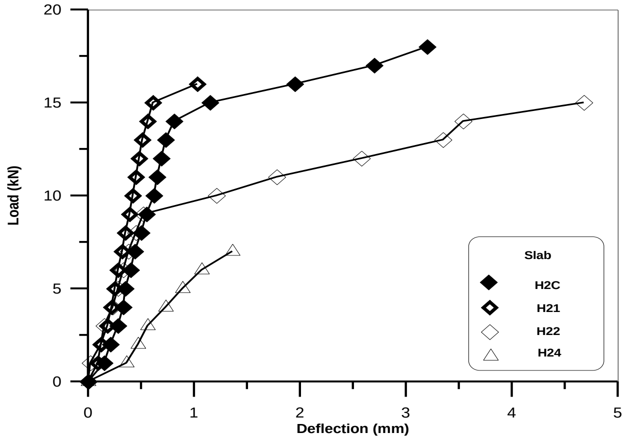

Figure (10) Load –Deflection relationship for flexural HSC slab specimens at different temperature levels.

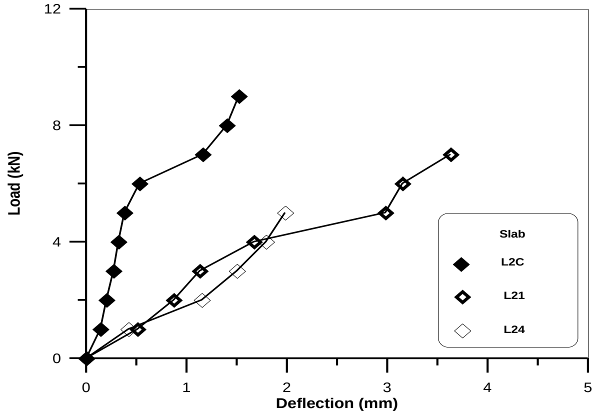

Figure (11) Load –Deflection relationship for flexural LWC slab specimens at different temperature levels.

The maximum deflection at the center of panel differs randomly with the temperature increase; the lowest values are for HSC slabs at the temperatures (room temp., 320° C, 450° C and 700° C) compared with NSC and LWC slabs.

However, the use of the LWC increases the value of the maximum deflection at temperature (320° C), and the value decreases at the temperatures (room temp. and 700° C), as compared with NSC.

3.9 Crack Pattern

When the load is applied to the reinforced flexural slab specimens with steel ratio (0.002), and the punching slab specimens N14 and H14 (exposed to 700° C), minor cracking at the central region takes place early in the test and first cracking of the tension surface occurs when the load reaches various percentages of the ultimate load depending on the temperature level. Four major cracks radiate from the center, extending well towards the edges of the panel.

As load increases, cracks along the diagonals become wider near the center of the panel; extending the full depth before loading at the panel is stopped .Cracks at the supports are also noticed.

At failure, yield – line mechanisms are fully developed .As temperature increases, the failure becomes faster and the yield – line becomes wider.

For the slab specimens N14 and H14, the cracks radiate as discussed above at final stages of loading. However, the yield – line width is less than the other slab specimens and is orthogonal in pattern and not diagonal. Figure (10) shows the crack patterns of the tested slab specimens.

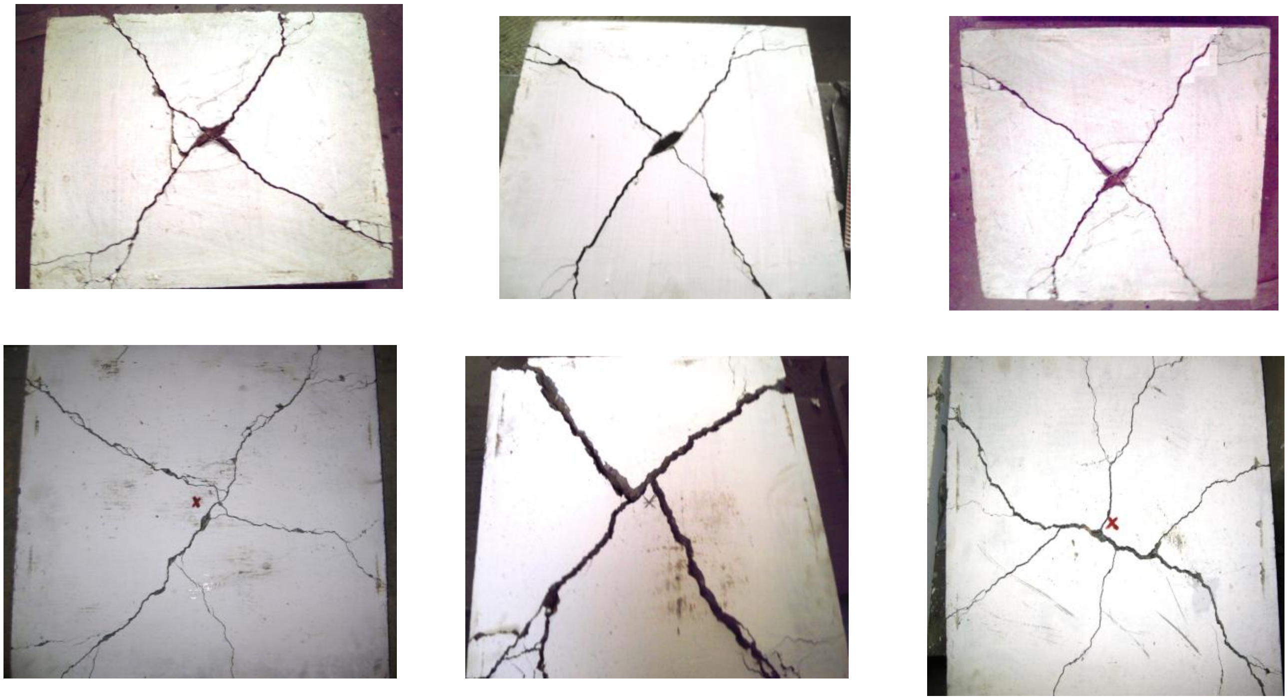

Figure (12) some of flexural slab specimens of groups N2, H2 and L2.

4. 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 ^{0}C 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 %) respectively.
2. The percentages reduction in ultimate load capacity for NSC slab specimens designed to fail in flexure after exposure to (450 ^{0}C and 700 ^{0}C) are about (9.1 % and 45.46 %) from the original load respectively. For HSC slab specimens designed to fail in flexural after exposure to (320 ^{0}C, 450 ^{0}C and 700 ^{0}C), the reductions are about (11.12 %, 33.14 % and 61.36 %) from the original load respectively. For LWC slabs designed to fail in flexure after exposure to (320 ^{0}C and 700 ^{0}C), the reductions are about (22.23% and 44.45%) from the original load respectively.
3. The maximum mid span deflection for all slab specimens designed to fail in flexure differs randomly with temperature increase, being lower, in general, for LWC slabs compared to NSC and HSC slabs respectively.
4. The load – deflection relationships are affected by the type of concrete slab, the high temperature, as follows:
   - 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.
5. Cracks are not visible on the top surfaces, however, they extend into the tension surface .These initial diagonal cracks, on further loading stages. Proceed to the yield – line cracks for the slab specimens failed by flexure.

6. It is observed that the shape of failure for the slab specimens failed in flexure, the yield – line mechanism is fully developed and as temperature increases failure becomes faster and the yield – lines become wider.

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