Experimental Study for Effect of Pervious Fire on Punching Shear Strength of Self Compacted Concrete flat plate Slabs

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Abstract

The effect of different pervious heating rates on punching shear strength of self compacting concrete flat plate slabs is studied as well as the effect of different heating rates on hot mechanical properties of SCC. Twelve square shaped slab specimens, divided into three groups with four sub groups each tested as well as a series of control specimens. The slab specimens and control specimens were subjected to high heating for at least one hour after reaching a specified temperature (100, 300 and 500^{O}C).

Experimental results show that the increase in compressive strength of self compacting concrete (SCC) improves the resistance to punching shear and this allows for higher forces to be transferred through the slab-column connection. Also, the results show that the heating rate (100^{o}C to 200^{o}C), does not significantly affect on ultimate shear capacity of high strength SCC. The results show reductions in ultimate shear capacity (3% to 26%) when the heating rates increased.

Keywords: Fire, Punching, Shear, Self compacting Concrete, Flat plate, Slabs.

الخلاصة

تاثيردرجات مختلفة من الحريق المسبق على مقاومة القص الثاقب للبلاطات الخرسانية الصفائحية ذاتية الرص تمت دراستها في هذا البحث. بالاضافة الى ذلك، تمت دراسة الخواص الميكانيكية للخرسانة ذاتية الرص بعد تعرضها لتاثيردرجات مختلفة من الحريق المسبق. تم فحص اثني عشرة بلاطة مربعة الشكل ، مقسمة الى ثلاثة مجاميع (اعتمادا على مقاومة الانضغاط) وكل مجموعة تحتوي اربعة نماذج (اعتمادا على درجة الحرق) هذا بالاضافة الى سلسلة من الفحوصات التي تم اجراءها على نماذج السيطرة . تم تعريض كلا من نماذج السيطرة و بلاطات الفحص الى درجات حرارة عالية لمدة لا تقل عن ساعة عند درجة الحرارة المطلوبة (100،300،500)درجة مئوية.

اظهرت النتائج المختبرية ان زيادة مقاومة الانضغاط للخرسانة ذاتية الرص يحسن مقاومة القص الثاقب وهذا يسمح بانتقال قوة اكبر من خلال المفصل الرابط بين العمود والبلاطة. كذلك، بينت النتائج ان درجات الحرارة (100،200)درجة مئوية لا تؤثر بصورة ملحوظة على المقاومة القصوى للقص الثاقب في الخرسانة ذاتية الرص عالية الانضغاط.

اظهرت النتائج، كذلك، حصول نقصان في المقاومة القصوى للقص الثاقب بمقدار (3% -26%) عندما درجات الحرق العالية

1-Introduction:

Flat plate slab structural systems have been widely used in building construction due to several advantages that include architectural design and fast construction methods. Since the flat plate slabs are supported directly by the columns, one of the major problems in such slabs is the punching shear failure at the connection between the slab and the column. Punching shear takes place due to high load concentration and relatively small depth (thickness) of a typical slab and its low capacity to transfer load to the columns by shear.

Several traditional techniques can be used to increase the shear strength of flat plate slabs such as bent bars, double-U bars, welded I-beams (shear head),…..etc.

Punching shear of flat plate slabs were studied by several researches [1,2] and several experimental investigations were conducted to increase the punching shear strength of slabs by using steel fiber reinforced concrete or high strength concrete or concrete polymer composite[3].

Instead of using conventional shear reinforcement or traditional techniques to increase shear capacity of flat slabs, the newest construction material (technique) which can be used in such cases includes moderate or high strength self compacting concrete.

SCC refers to a "new" type of concrete mixture, characterized by high resistance to segregation, which can be cast without compaction or vibration [4, 5] .

The use of SCC will lead to economic benefits because of a number of factors such as, self leveling, filling all voids, no segregation, ease of delivery, high performance, reduction of labor costs, reduced equipment on the jobsite, improved labor safety, shortening construction time….etc.

When the concrete members are subjected to high temperature (greater than $300\,^{O}C$), the compressive strength is reduced significantly[6]. Pervious researches show that the loss in compressive strength for normal strength SCC was significantly higher than for high strength SCC when the temperature ranges below ($400\,^{O}C$).

The objective of the research is to specify the effect of heated SCC on punching shear behavior of flat plate slabs. Also, the effect of different heating rates on hot mechanical properties of SCC is studied.

2-Description of Experimental Program

2-1 Details of Test Specimens

Three test slab groups were manufactured, each of which consisted of four slab specimens identical in size and concrete strength but different in heating rates. All slab specimens were square shaped and having a dimension of (450mm, 450mm and 50mm) for width, length and thickness respectively; see Table (1) and Figure (1). The slab specimens were made with three different concrete mixes (30MPa, 50MPa and 70MPa) and subjected to heating rate of (25, 100, 300 and 500 ^{O}C) before testing. The dimensions and reinforcement were kept constant thoughtout this work. It may be noted that the term "high strength self compacting concrete" refer in this study to concrete mix (S70). Each slab was designated in a way to refer to concrete strength (S30, S50 and S70) and heating rate (T25, T100, T300 and T500 ^{O}C). Therefore, the slab (S70T300) is a slab specimen made with (70MPa) concrete compressive strength and subjected to previous temperature of (300 ^{O}C).

Table (1) Properties and Description of Tested Slabs

Slab Shape	Group	Slab Designation	f_{cu} MPa	T (^{o}C)	w (mm)	l (mm)	t (mm)	Reinforcement
Square	Group-1	S30T25*	30	25	450	450	50	WWF with ϕ 6 mm@ 75 c/c in each direction
		S30T100		100				
		S30T300		300				
		S30T500		500				
	Group-2	S50T25*	50	25				
		S50T100		100				
		S50T300		300				
		S50T500		500				
	Group-3	S70T25*	70	25				
		S70T100		100				
		S70T300		300				
		S70T500		500				

*Reference Slabs

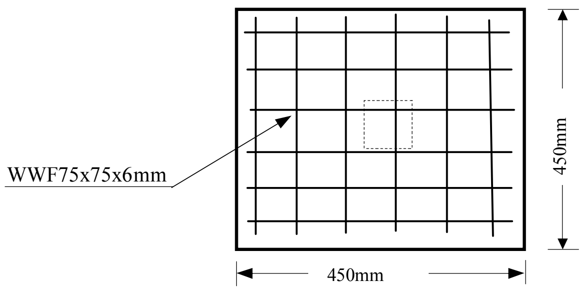

Figure (1) Dimensions and Reinforcement of Tested Slabs

All slabs are simply supported along all edges and subjected to single point load applied at the center of gravity of each slab. The applied load is transformed from testing machine through a central column of dimensions (40X40mm). It may be noted that, each group is divided into four sub group (slab specimens) based on pervious heating rate.

2-2 Materials

In manufacturing the test specimens, the following materials are used: ordinary Portland cement (Type I); crushed gravel with maximum size of (10mm); natural sand from Al-Ukhaider region with maximum size of (4.75mm) and fineness modulus (3.18); Limestone powder (L. S. P.) with fineness (3100 cm2/gm), high water reducing superplasticizer; clean tap water was used for both, mixing and curing. The concrete mix proportions are shown in Table (2).

The steel reinforcement mesh consist of welded wire fabric (WWF); each wire have (5mm) diameter, yield strength (fy) of (310 MPa), ultimate tensile strength (fu) of (530 MPa) and (75 mm) c/c spacing in each way. A clear cover of (5mm) was provided below the mesh. It may be noted that the steel reinforcement were design to ensure the tested specimens to fail by punching shear.

For each slab specimen, only one sample was manufactured. While, for control specimens (cubes and prisms), an average of three samples (per mix per temperature) by using (100x100x100mm) cubes were used for compressive strength test and an average of two samples (per mix per temperature) by using (100x100x500mm) prisms were used for modulus of rupture test. Both, slab specimens and control specimens were cured under the same conditions (for 28 days) and heated in an oven at the same time, after (7days) beyond the end of curing.

Table (2) Concrete Mixes

Material	Mix Designation		
	S30	S50	S70
Cement (kg/m^3)	367	474	540
Limestone Powder (kg/m^3)	195	105.3	64
Sand (kg/m^3)	841	807.4	880
Gravel (kg/m^3)	791	784	780
Water (L/m^3)	183	180	155
Superplasticizer (L/m^3)	4	8.1	18

2-3 Test Measurements and Instrumentation

Hydraulic universal testing machine (MFL system) was used to test the slab specimens as well as the control specimens. Ovens of high heating (greater than 700 ^{O}C) were used to reach the specified rates of temperature.

Central deflection has been measured by means of (0.01mm) accuracy dial gauge (ELE type) and (30mm) capacity. The dial gauges were placed underneath the bottom face at the center.

2-4 Test Results of Specimens

Properties of the SCC in the fresh state were measured and are presented in Table (3). Also, test results of mechanical properties of hardened concrete specimens are summarized in Table (4). Compressive strength was carried out on (100x1001x100mm) cubes and tensile strength in flexure (modulus of rupture) was carried out in accordance with ASTM-C78 [7].

Table (3) Properties of the SCC in the Fresh State

Mix Designation	Slump Flow (mm/sec)	L-Box (Sec.)	T20 (Sec.)	T40 (Sec.)	T50 (Sec.)
S30	**770**	**1.0**	**1.5**	**2.2**	**3.5**
S50	**720**	**0.93**	**2.2**	**4**	**4.1**
S70	**658**	**0.82**	**5.5**	**6.3**	**8.1**

Table (4) Mechanical Properties of Concrete at different Temperature

Property (MPa)	Mix Designation	Temperature			
		25^oC	100^oC	300^oC	500^oC
(f_{cu})*	S30	32.5	31.0	28.5	25.8
	S50	48.8	48.1	45.3	40.1
	S70	68.5	68.3	62.7	58.4
(f_r)**	S30	4.5	4.4	4.1	3.8
	S50	7.0	6.9	6.8	5.9
	S70	9.5	9.3	8.8	8.3

***Average of three samples (per mix per temperature) by using (100x100x100mm) cubes**
**** Average of two samples (per mix per temperature) by using (100x100x500mm) prisms.**

2-5 Test Procedure

In order to specify the change in the compressive strength of concrete after heating at specified temperature (100, 300 and 500 ^oC), the tested specimens were put in an oven of high heating. After heating to high temperature for at least one hour, the heating was stopped; the temperature was reduced gradually and the specimens were tested under normal conditions. It may be noted that the reference slabs (S30T25, S50T25 and S70T25) were tested directly at laboratory conditions (at 25 ^oC).

All slab specimens were tested using universal testing machine (MFL system) with monotonic loading to ultimate states. The tested slabs were simply supported and loaded with a single-point load; refer to Figure (2). The slabs have been tested at the age of (28) days. The slab specimens were placed on the testing machine and adjusted so that the centerline, supports, point load and dial gauge were in their correct or best locations.

Loading was applied slowly in successive increments. At the end of each load increment, observations and measurements were recorded for the midspan deflection and crack development and propagation on the slab surface. When the slabs reached advanced stage of loading, smaller increments were applied until failure, where the load indicator stopped recording any more increase in load and the deflections increased very fast without any increase in applied load.

The developments of cracks (crack pattern) were marked with a pencil at each load increment.

Figure (2) Setup of Tested Specimens

3-Results and discussion

3-1 Control Specimens

3-1-1 Compressive Strength

As shown in Table (4) and Figure (3), for the concrete mix (S30), the ultimate compressive strength decreased by (5%), (14%) and (21%) when the rate of heating increased to (100 ^oC), (300 ^oC) and (500 ^oC) respectively. For the concrete mix (S50), the ultimate compressive strength values are decreased by (1%), (7%) and (18%) when the rate of heating increased to (100 ^oC), (300 ^oC) and (500 ^oC) respectively. In contrast for concrete mix (S70), the ultimate compressive strength decreased by (0%), (8%) and (15%) when the rate of heating increased to (100 ^oC), (300 ^oC) and (500 ^oC) respectively. This means, with increasing the compressive strength of SCC resistance to high temperature increased. This may be due to high density, homogeneity and durability of high strength SCC.

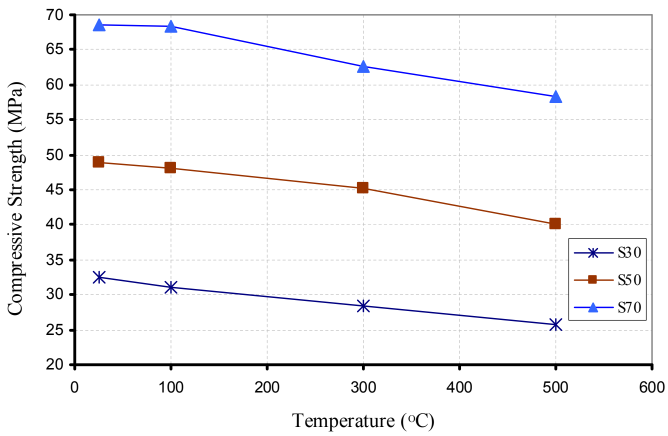

Figure (3) SCC Compressive Strength-Temperature Relationship

3-1-2 Modulus of Rupture

Experimental results, Table (4) and Figure (4), show that the modulus of rupture for the concrete mix (S30) decreased by (2%), (9%) and (16%) when the rate of heating increased to ($100^{o}C$), ($300^{o}C$) and ($500^{o}C$) respectively.

For the concrete mix (S50), the modulus of rupture decreased (2%), (9%) and (16%) when the rate of heating increased to ($100^{o}C$), ($300^{o}C$) and ($500^{o}C$) respectively. In contrast for concrete mix (S70), the modulus of rupture are decreased (2%), (7%) and (13%) when the rate of heating increased to ($100^{o}C$), ($300^{o}C$) and ($500^{o}C$) respectively.

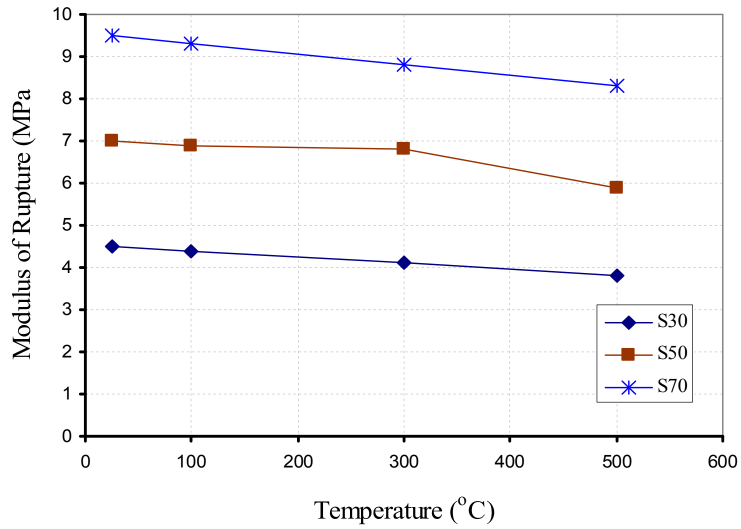

Figure (4) SCC Modulus of Rupture-Temperature Relationship

3-2 Slab Specimens

3-2-1 General Behavior

Photographs of the tested slabs are shown in Figure (5) and test results are given in Table (5). As mentioned before, all tested slabs were designed to fail in punching shear. Generally, as the load increase, radial cracks start to appear and extend from that perimeter toward the slab edges.

At the same time the cracks increase in number at the center region of the slab. A complete failure occurred by increasing the load.

Table (5) Ultimate, Cracking load and type of Failure of Tested Slabs

Slab Shape	Group	Slab Designation	P_u (kN)	P_{ui}/P_{ur}	P_{cr} (kN)	P_{cr}/P_u	Failure Mode
Square	Group-1	S30T25*	37	1.00	7.5	0.20	Punching Shear
		S30T100	36	0.97	7.5	0.21	
		S30T300	35	0.95	7.0	0.20	
		S30T500	32	0.86	8.0	0.25	
	Group-2	S50T25*	50	1.00	7.0	0.14	
		S50T100	39	0.78	7.0	0.18	
		S50T300	38	0.76	7.0	0.19	
		S50T500	37	0.74	7.5	0.20	
	Group-3	S70T25*	50	1.00	7.0	0.14	
		S70T100	50	1.00	7.0	0.14	
		S70T300	43	0.86	7.0	0.16	
		S70T500	42	0.84	7.0	0.17	

* Reference Slabs

3-2-2 Ultimate and Cracking Loads

Experimental results show reduction in ultimate shear capacity when the heating rates changed from (25^oC) to (100^oC), (300^oC) and (500^oC). For the first group, (S30), the reductions in ultimate shear capacity are (3%), (5%) and (14%), when the rate of heating increased to (100^oC), (300^oC) and (500^oC) respectively. For the concrete mix (S50), second group, the ultimate shear capacity decreased (22%), (24%) and (26%) when the rate of heating increased to (100^oC), (300^oC) and (500^oC) respectively. For the concrete mix (S70), third group, the shear capacity is decreased by (14%) and (16%) when the rate of heating increased to (300^oC) and (500^oC) respectively. In contrast for slab specimen (S70T100), when the rate of heating changed from (25^oC) to (100^oC), no change in strength was recorded in comparison with reference slab (S70T25). This means, the low heating rate does not affect ultimate capacity of high strength SCC, (S70).

As shown in Table (5), the cracking loads for each group are nearly the same, this means the cracking loads depend on concrete strength and are not affected by rate of heating. While, the ultimate load capacity depends mainly on both, concrete strength and rate of heating.

Generally, all tested slab specimens exhibit high reduction in shear capacity at high rate of heating.

3-2-3 Failure Mode

All the tested specimens failed in punching shear, the punching shear failure occurred by development of cracks and these cracks progressed rapidly and led to failure and as a result crushing of the concrete, Figure (5).

3-2-4 Crack Pattern

The first crack appears around the sides of the column on the tension face of the slab and other cracks form at the central region of the slab. By increasing the load, these cracks widen and increase in number. At ultimate load, punching shear failure occurs suddenly. Figure (5) illustrates crack patterns and failure modes of the tested slab specimens.

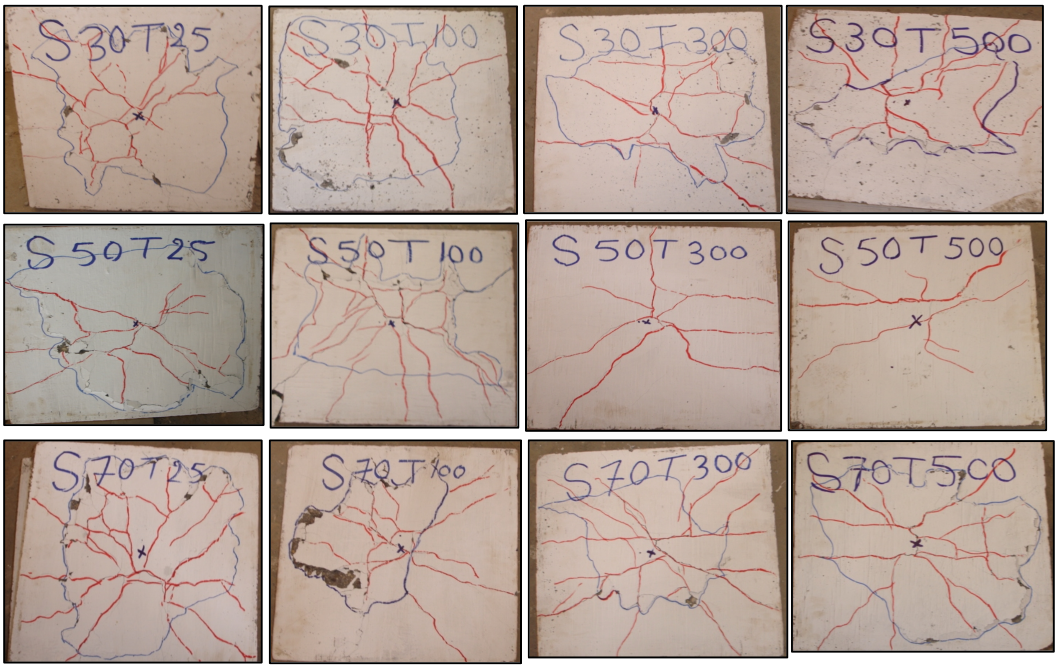

Figure (5) Crack Patterns of Tested Specimens at Failure (bottom face)

3-2-5 Area of the Failure Zone

The perimeters of the punching shear failure zones are measured and presented in Table (6). The calculated perimeters of critical section were done based on ACI318-05 (Article 11.12.1.2).

As shown in Table (6), the ratio of calculated to measured perimeters of critical section is about (23%-30%), this means the assumption of ACI-05 (Article 11.12.1.2)**[8]** underestimates values and there may be a need to reconsider SCC requirements.

The crack angle of punching shear was found to be approximately between (22) to (36) degrees. It may be noted that, for specimens made with high strength concrete (S70), the crack angle was relatively less (crack angle of approximately 22 degrees).

Table (6) Failure Characteristics of Tested Slabs

Slab Shape	Group	Slab Designation	Measured Perimeter (mm)	Calculated Perimeter# (mm)	(bo)*cal.*/(bo)*m*
Square	Group-1	S30T25*	1320	328	0.25
		S30T100	1280		0.26
		S30T300	1290		0.25
		S30T500	1170		0.28
	Group-2	S50T25*	1450		0.23
		S50T100	1330		0.25
		S50T300	1180		0.28
		S50T500	1080		0.30
	Group-3	S70T25*	1220		0.27
		S70T100	1080		0.30
		S70T300	1080		0.30
		S70T500	1280		0.26

ACI 318-05 (Article 11.12.1.2)

d=h-$0.5d_b$-*cover*=50-0.5*6-5= 42mm

3-2-6 Load – Deflection Behavior

Load-Deflection curves under the center of loaded area for tested specimens were constructed and presented in Figure (6) to Figure (8). Load-Deflection curves of each group and comparison between the group specimens are shown in Figure (6). Generally, all tested specimens show similar behavior throughout the testes. The curves show the ultimate loads at which the tested specimens reached before failure and clearly, the reference slabs specimens (S30T25, S50T25 and S70T25) exhibits greater capacity in comparison with others. Also, the curves show the reduction in shear capacity due to pervious heating.

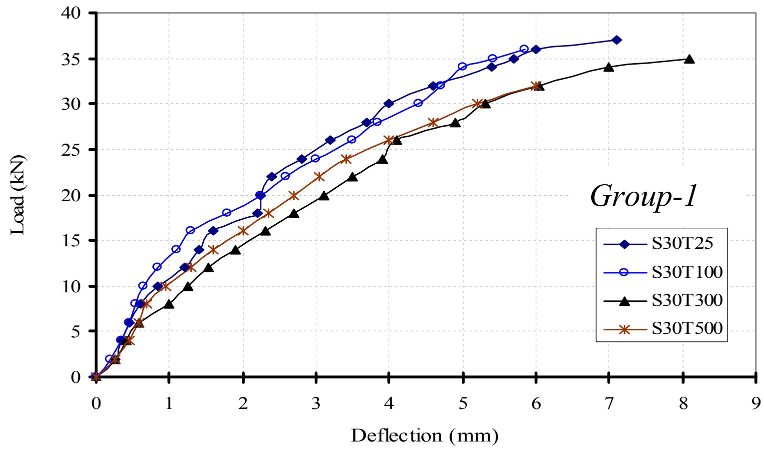

Figure (6) Load-Deflection Curves for Tested Slabs of Group-1

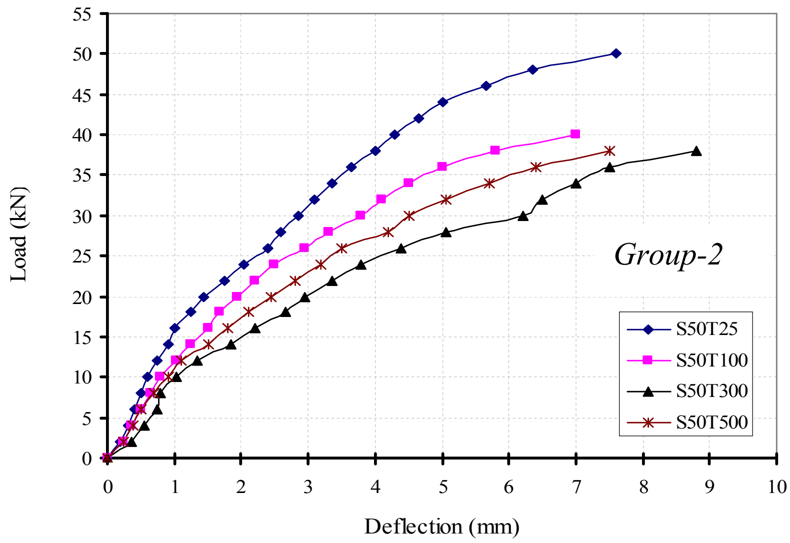

Figure (7) Load-Deflection Curves for Tested Slabs of Group-2

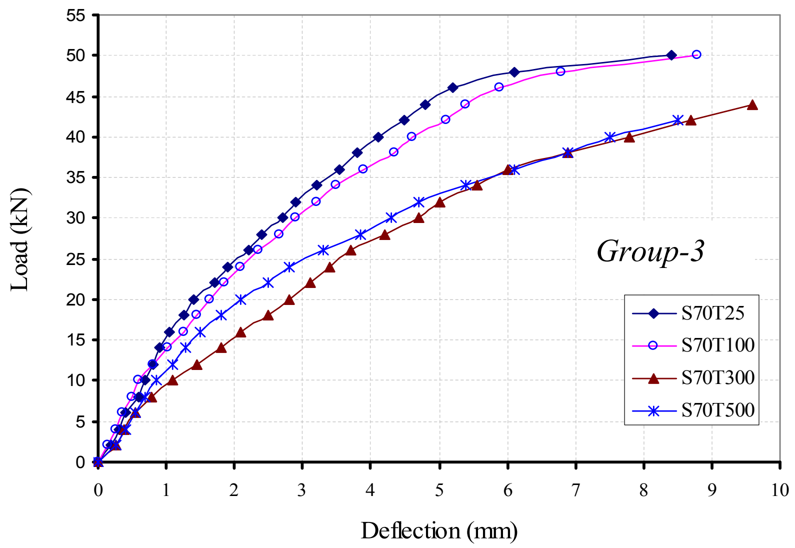

Figure (8) Load-Deflection Curves for Tested Slabs of Group-3

4-Conclusions

From the pervious discussions, the following points are reached:

1- Due to high density, homogeneity of SCC, the resistance to high temperatures increased with increasing compressive strength.

2-With increasing compressive strength of SCC the resistance to the punching shear improved and this allowed to higher forces to be transferred through the slab-column connection.

3- The cracking loads for all groups are approximately similar, and this means that the cracking loads depend mainly on concrete strength and are not affected by rate of heating. Also, the ultimate capacity depends mainly on both, concrete strength and rate of heating.

4- All tested slab specimens exhibit reduction in shear capacity at high rate of heating(100 ^oC to 500 ^oC), the shear capacity decreased by (3%-14%), (22%-26%) and (0%-16%) for the first, second and third group respectively.

5- The low heating rate (100 ^oC to 200 ^oC), does not significantly affect on ultimate shear capacity of high strength SCC.

6- Ratio of calculated to measured perimeters of critical sections is about (23%-30%), this means the assumption of ACI 318-05 (Article 11.12.1.2) gives underestimated values and there may be a need to be reconsider SCC requirements.

5-Notation

b_o= Perimeter of critical section;

$(b_o)_{cal}$=Calculated perimeter of critical section;

$(b_o)_m$= Measured perimeter of critical section;

f_{cu} = Ultimate cube compressive strength;

f_r = Modulus of rupture;

f_y = Yield strength of reinforcement bars;

f_u = Ultimate tensile strength of reinforcement bars;

l = Slab length;

P_u= Ultimate load;

P_{cr}= Cracking load;

P_{ui}= Ultimate load of considered slab;

P_{ur}=Ultimate load of reference slab;

t = Slab thickness;

T= Temperature;

w = Slab width;

ϕ = Diameter of reinforcement bars.

6-References

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