Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (39) No. (3) july, 2017

Effect of fire on structural behavior of Normal and High Strength Concrete beams

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ملخص البحث

يهدف هذا البحث إلى عمل دراسة مقارنة بين تأثير الحريق على سلوك الكمرات الخرسانية المسلحة ذات المقاومة العادية والمقاومة العالية و خاصة بعد زيادة إستخدام الخرسانة عالية المقاومة فى المنشأت الخرسانية و خصوصا المبانى العالية. تم دراسة السلوك الانشائى لعدد 16 كمرة خرسانية مسلحة ذات ابعاد حقيقية وهى (0.15*0.30*2.80م) تحت تأثير حمل الإنحناء حتى مرحلة الإنهيار وتم إختبار أربعة كمرات منهم فى حرارة الغرفة العادية (عينات قياسية) وباقى الكمرات الاثنى عشر الاخرى تم تعريضهم لدرجة حرارة 600 درجة مئوية و تبريدهم قبل إختبارهم تحت تأثير مجموعة من العوامل تتمثل فى تأثير مقاومة الخرسانة(300-600 كجم /سم2) و نوع الاطفاء للكمرات (هواء و ماء) و زمن الحريق الذى تتعرض له الكمرات (3 و 5 ساعات) و قد أوضحت النتائج أن حمل الإنهيار للكمرات المعرضة للحريق مقارنة بالكمرات القياسية يقل بنسبة 23.2% فى حالة الكمرات الخرسانية عالية المقاومة وتصل هذه النسبة إلى 26% فى الكمرات الخرسانية ذات المقاومة العادية وكذلك يقل حمل الإنهيار أكثر عند التبريد بالماء بدلا من الهواء و كذلك عند زيادة زمن الحريق و تقل مقاومة التماسك بين حديد التسليح والخرسانة و معامل المرونة للخرسانة المعرضة للحريق عن غيرها الغير معرضة للحريق (القياسية) و تتناسب مقاومة الضغط للخرسانة المعرضة للحريق تناسبا عكسيا مع سمك غطاء الخرسانة .

1. ABSTRACT

This paper investigates and evaluates experimentally the structural behavior of high strength concrete (HSC) beams exposed to fire and compares it with that of Normal strength concrete (NSC) beams. Sixteen full scale beams (150 x 300 x 2600) mm were tested under flexural monotonic loading up to failure. Out of the tested beams, four of them were tested at room temperature (control specimens), while the other twelve specimens were subjected to fire in a furnace and after cooling they were tested to failure under flexural monotonic loading in order to measure their residual loading capacities. The main investigated parameters are: concrete compressive strength (300 or 600 kg/cm^2); the concrete cover thickness (3 or 5 cm); the degree of temperature (room temperature or 600 ^{o}c); the type of cooling (air or water); and the fire exposure time (3 or 5 hours). Test results showed that the concrete compressive strength decreases significantly as the exposure time to fire increases. The average reduction in the residual concrete compressive strength is more pronounced in HSC than NSC. Thicker concrete cover is recommended for beams subjected to fire especially in case of HSC beams. Air cooling after exposure to fire is preferable from the structural point of view.

Keywords— Experimental, Fire, High Strength Concrete Beams, Monotonic Loading.

2. INTRODUCTION

Recently, the use of HSC gains increasing popularity especially in high rise buildings. Therefore, many research efforts have been devoted for understanding and evaluating the properties and the structural behavior of HSC elements and comparing them to those of NSC ones (e. g. [1]-[4]).

On the other hand, many researches have been done on the structural behavior of NSC beams under fire. Moetaz M. El-Hawary [5] presented an experimental study to investigate the effect of fire exposure time on the flexural behavior of RC beams. Moetaz M. El-Hawary [5] concluded that the deflections of beams subjected to fire increase and the loading capacities decrease as the fire exposure time increases. In an experimental study to investigate the effect of fire up to 900°C on RC beams, Rahul P [6] concluded that the flexural strength of beams decreases as the temperature increases. Moreover, Rahul P [6] observed that the thicker concrete cover is better for the flexural strength at higher fires.

However, few researches have focused on investigating the structural behavior of HSC beams under fire and comparing them to NSC beams of similar conditions. E. G. Choi and Y. S. Shin [7] studied experimentally the effects of concrete compressive strength and cover thickness on the structural behavior of RC beams under fire. E. G. Choi and Y. S. Shin [7] concluded that the relationships between time and temperature distributions in the beam sections are very similar and are unrelated to the strength of the concrete. In addition, E. G. Choi and Y. S. Shin [7] found that the rates of deflection increase for both normal strength and high strength concrete beams is very similar before spalling but becomes remarkably high for high strength concrete beams after spalling. B. Kiani et al. [8] reported the results of the residual compressive strength on fiber reinforced mortar at fire. Polypropylene and cellulose fibers were investigated. B. Kiani et al. [8] concluded that the inclusion of fiber in the mortar mix leads to an improvement in compressive strength and a better resistance to heating effects. For the heated mortars, the use of cellulose fiber resulted in higher residual compressive strength than the use of polypropylene fiber.

This study was intended to investigate the effects of compressive strength, cover thickness, type of cooling, and fire exposure period on the structural behavior of HSC and NSC beams under fire. Test results were investigated by the residual concrete compressive strength, the residual loading capacity, crack patterns, and the deflection caused by elevated temperature.

3. Experimental Program

As shown in Fig. 1 and Table I, sixteen full-scale beams (150 x 300 x 2600) mm were tested under flexural monotonic loading up to failure. Four beams were tested at room temperature (control specimens), while the other twelve specimens were subjected to an elevated temperature in a furnace and after cooling they were tested to failure under four-point monotonic loading. The specimens were classified into two groups according to the difference in concrete compressive strength (300 or 600 kg/cm2). Each group was sub-classified into two sub-groups according to the cover thickness (3 or 5 cm). Each sub-group was divided into two sections according to the degree of temperature (room temperature or 600 oc). Finally, some sections were divided into two sub-sections according to the type of cooling (air or water) and fire exposure time (3 or 5 hours). In order to measure steel strains at critical sections, strain gauges were attached to the bottom and top steel rebars at midspan before casting the beams. Moreover, three thermocouples were fixed in the center section of the beams. As shown in Fig. 2, the thermocouples were fixed at distances of 3, 7 and 10 cm from the edge end of the specimens in order to measure the temperature distribution through the beam cross section during the fire test.

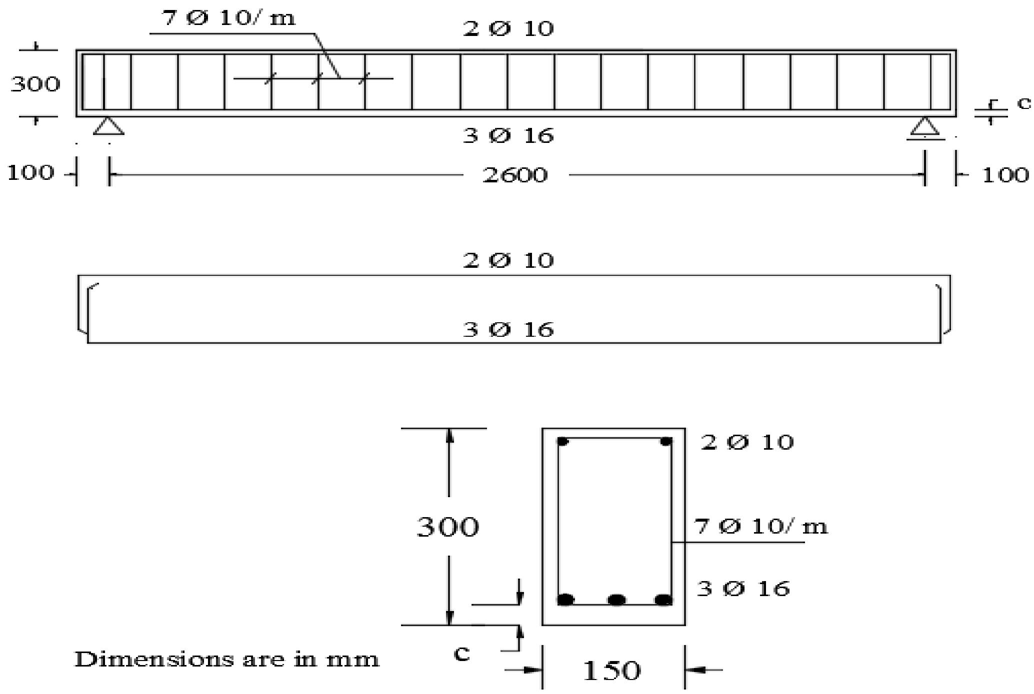

Fig. 1 Details of the tested beams

TABLE I : Tested Beams Details

Beam. No	F_{cu} (Kg/Cm^2)	Cover thickness (cm)	Degree of temperature (^oc)	Type of cooling	Time of heating (hours)
A1	300	3	Room Temp.	Control Specimen	Control Specimen
A2		3	600	Air	3
A3		3	600	water	3
A4		3	600	water	5
B1		5	Room Temp.	Control Specimen	Control Specimen
B2		5	600	Air	3
B3		5	600	water	3
B4		5	600	water	5
C1	600	3	Room Temp.	Control Specimen	Standard Specimen
C2		3	600	Air	3
C3		3	600	water	5
C4		3	600	Air	5
D1		5	Room Temp.	Standard Specimen	Standard Specimen
D2		5	600	Air	3
D3		5	600	water	5
D4		5	600	Air	5

In order to predict the ultimate compressive strength of the applied concrete, three standard concrete cubes 150 × 150 ×150 mm were tested at room temperature after 28 days. On the other hand, in order to predict the residual ultimate compressive strength after fire exposure, four sets of three standard cubes for each case (NSC and HSC) were burned at 600 °C in the furnace with the concrete beams at (3 or 5 hours); then cooled by (air or water) before testing. Table II presents the average results of these cubes.

Fig. 2 Location of thermocouples at beams midspan

TABLE II :Residual average Concrete Comp. strength after 28 days (kg/ cm2)

	At Room Temp.	After 3 hrs of fire exposure		After 5 hrs of fire exposure	
		Air cooling	Water cooling	Air cooling	Water cooling
NSC	322	290	245	286	234
HSC	605	425	342	341	300

4. Test Setup, Procedure and Measurements

The test setup and instrumentation is shown in Fig. 3. Before testing the beams, twelve of them were subjected to an elevated temperature in a furnace and then cooled as explained in Table 1. The furnace has been designed to present a time– temperature curve according to the ISO-834 standard time temperature curve shown in Fig. 4. The furnace used in this research work is a part of the reinforced concrete institute laboratory in National Housing and Building Research Center (NHBRC) in Cairo. The clear space inside the furnace is 200 cm x 200cm x 100 cm.

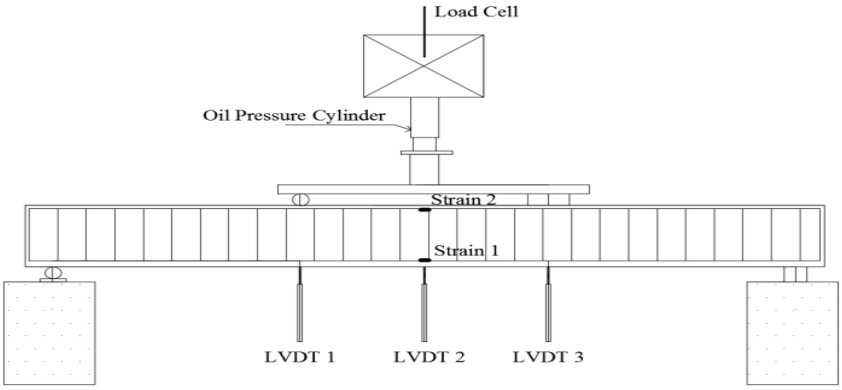

Fig. 3 Test setup and instrumentation

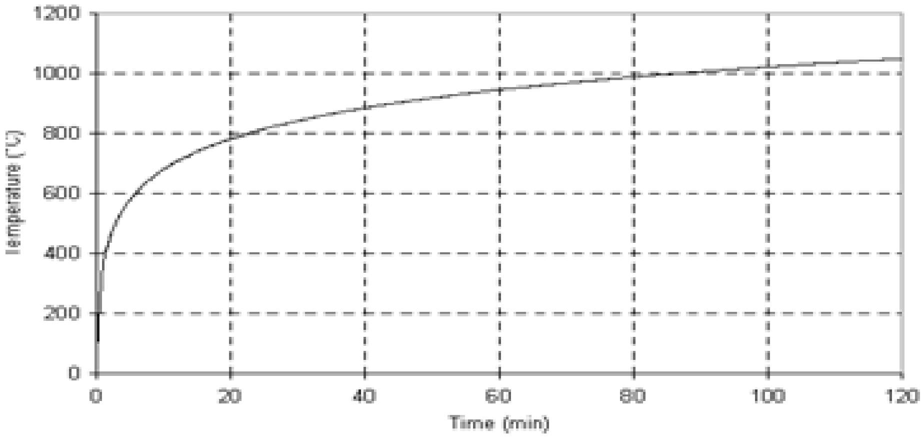

Fig. 4 Standard ISO 384 firing curve

5.Test Results and Discussion

5.1 Residual Concrete Compressive Strength

As shown in Table II and as interpreted in Table III, the residual concrete compressive strength after fire exposure is much less than the concrete compressive strength at room temperature. The average reduction in residual concrete compressive strength is more pronounced in HSC than NSC. Also, the average reduction in residual concrete compressive strength is directly proportional to the fire exposure period. Water cooling is more harmful to the residual concrete compressive strength than air cooling.

TABLE III
Average percentage reduction in residual Concrete Comp. strength

	Avg. Comp. Strength at Room Temp. (Kg/ cm2)	After 3 hours of fire exposure		After 5 hours of fire exposure	
		Air cooling	Water cooling	Air cooling	Water cooling
NSC	322	9.9 %	23.9 %	11.2 %	27.3 %
HSC	605	29.8 %	43.5 %	43.6 %	50.4 %

5.2 Loading Capacity of the tested beams

Table IV presents the ultimate loads and the corresponding maximum midspan deflection of the tested beams. It is obvious that all beams exposed to fire have lower loading capacities and higher midspan deflections than those of the corresponding control specimens. Fig. 5 presents the percentage reduction in ultimate loading capacities due to fire exposure. Columns with diagonal lines represent NSC beams while solid columns represent their HSC counterparts. It is noted from the chart that the percentage reduction in the ultimate loading capacity of beam A2 is less than that of beam C2, while the ultimate loading capacity of beam B2 is higher than that of beam D2. This may indicate the value of using thicker concrete cover when using HSC. The percentage reduction in the ultimate loading capacities of beams A4 and C3 are almost similar. The same observation applies for beams B4 and D3. This may indicate that the concrete compressive strength has no effect on the percentage reduction of ultimate loading capacity for beams with long fire exposure period.

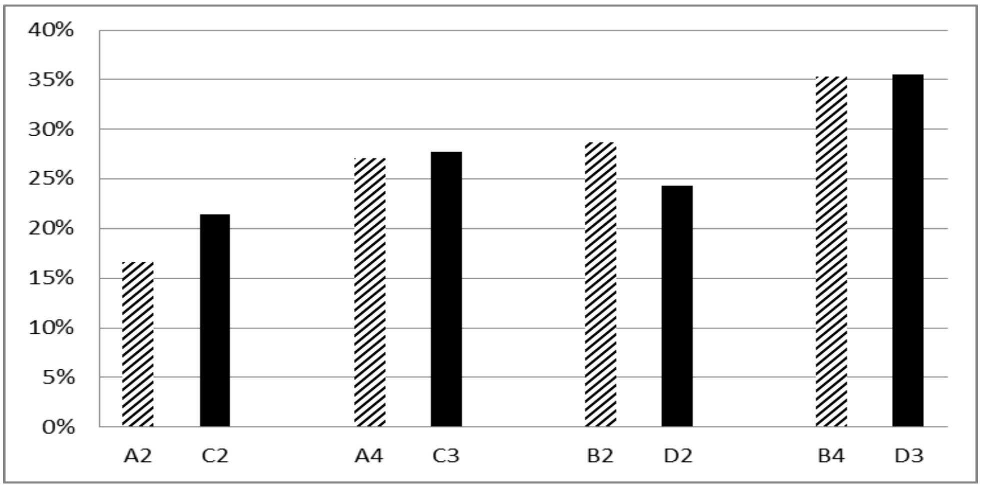

Fig. 5 Percentage reduction in ultimate loading capacity due to fire exposure.

TABLE IV :Ultimate Load and max. midspan deflection of the Tested Beams

Beam. No	Ultimate Load (ton)	% Reduction in Ultimate Load	Max Midspan Deflection (mm)
A1	19.34	-----	26.32
A2	16.12	16.6 %	45.70
A3	14.24	26.4 %	29.03
A4	14.11	27.0 %	24.86
B1	17.09	-----	19.70
B2	12.18	28.7 %	31.56
B3	12.32	27.9 %	26.46
B4	11.06	35.3 %	29.66
C1	21.96	-----	24.32
C2	17.25	21.4 %	25.55
C3	15.88	27.7 %	26.15
C4	14.56	33.7 %	34.24
D1	18.54	-----	17.64
D2	14.03	24.3 %	32.36
D3	11.96	35.5 %	22.60
D4	12.79	31.0 %	35.81

5.3 Cracks Patterns

Fig. 6 presents a sample of cracks patterns of some beams at failure. Smaller Crack widths are observed in control beams, while wider cracks are observed in beams exposed to fire. Width and spread of cracks in NSC beams are higher than those of HSC beams. Prior to failure, some HSC beams were prone to spalling.

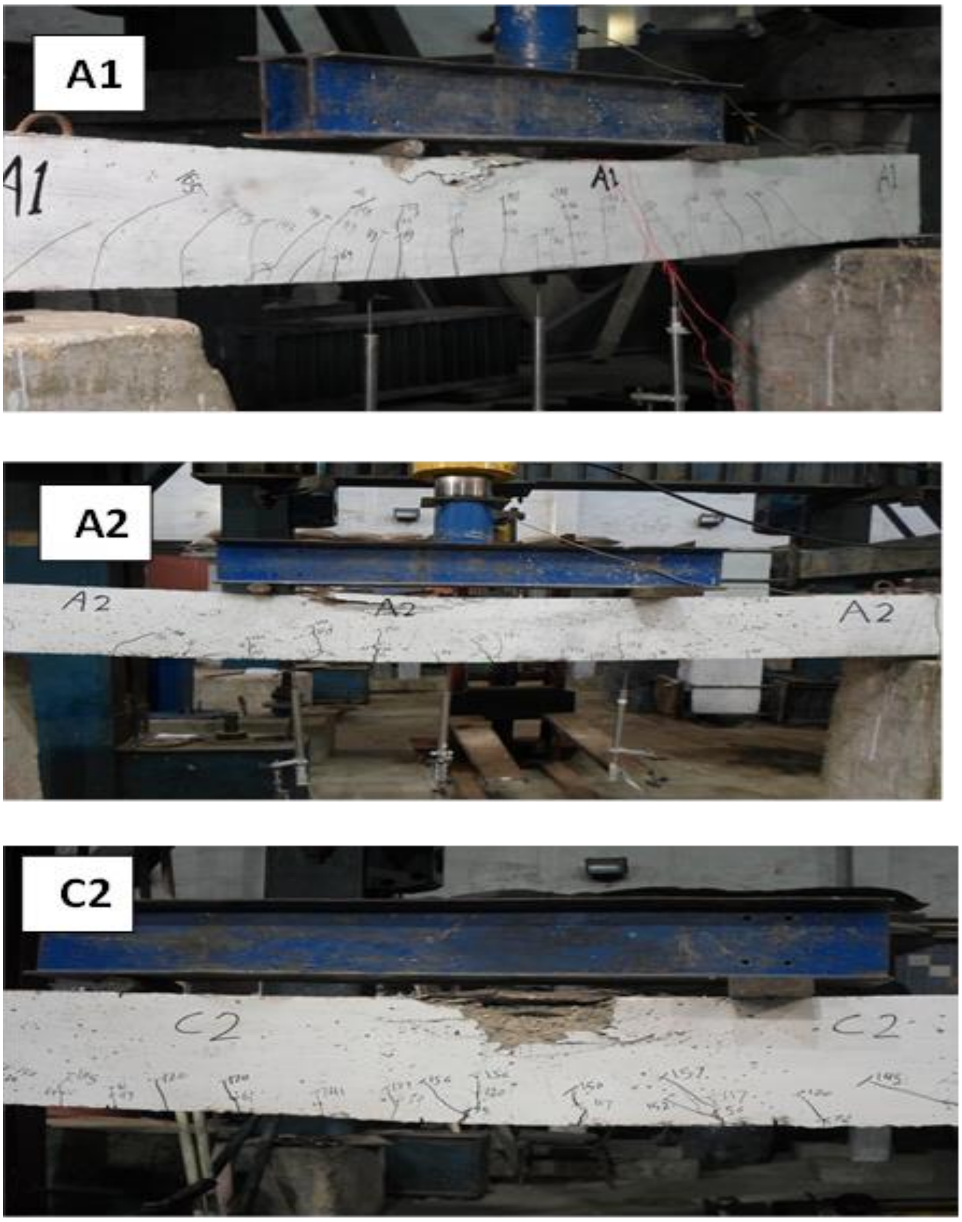

Fig. 6 Cracks Patterns of beams A1, A2, and C2 at failure.

5.4 Load- Deflection Behavior of the tested beams

Fig. 7 shows typical charts for the relationship between the load and the corresponding midspan deflections for some of the tested beams. As it is indicated by the charts, the relationship is almost linear at the elastic stage and the slopes of the curves decrease as the fire exposure time increases. As the fire exposure period increases and the concrete cover thickness decreases, the deflection of the tested beams increases. After cracking, deflections increased greatly with load up to a point just after yielding of the tensile steel.

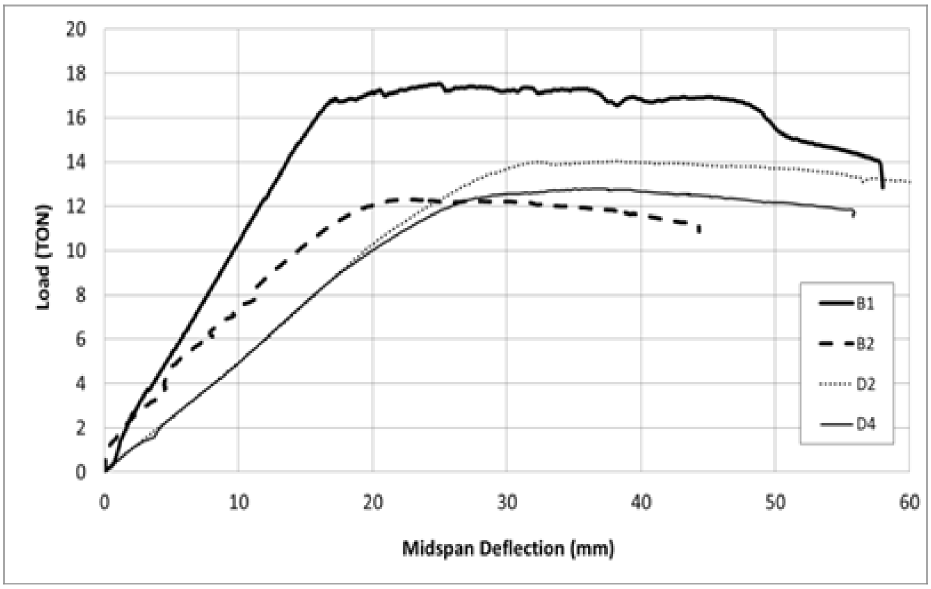

Fig. 7 Load-Deflection curves for beams B1, B2, D2, and D4.

6. Conclusion

Based on the above analysis and discussions, the following conclusions are drawn:

1- The residual concrete compressive strength after fire exposure is much less than the concrete compressive strength at room temperature. The average reduction in residual concrete compressive strength is more pronounced in HSC than NSC
2- Thicker concrete cover is recommended for beams subjected to fire especially in case of HSC beams.
3- The deflection of beams subjected to fire is directly proportional to the fire exposure period and it is inversely proportional to the cover thickness.
4- Concrete compressive strength has no effect on the percentage reduction of ultimate loading capacity for beams with long fire exposure period.

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