ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

FLEXURAL CAPACITY OF HIGH PERFORMANCE SELF COMPACTING RC BEAMS UNDER DIRECT FIRE

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ABSTRACT

This work analyses the structural behavior of high performance self compacting reinforced concrete (RC) beams under direct fire. Concrete strength of about 130 MPa was investigated. Six reinforced concrete beams represents three types of concrete mixes were investigated. The first mix was high performance self compacting concrete (HPSCC) without fibers. The second mix was HPSCC with the presence of steel fibers (SF). The third mix was HPSCC with hybrid fibers, SF and two types of polypropylene fibers (micro-polypropylene and polyolefin). Three beams representing the three mixes were tested at room temperature without exposure to fire. The other corresponding three beams were tested under direct fire, while they were loaded at 45% from the fracture load of the corresponding three beams tested at room temperature to failure. All beams were tested under 3-points bending. Experimental results clearly indicated the superior effect of adding hybrid fibers to such concrete in reducing explosive spalling and increasing flexural capacity of RC beams when exposed to direct fire.

يتناول هذا البحث السلوك الأنشائى للكمرات الخرسانية المسلحة والمصنوعة من خرسانة عالية الآداء وذاتية الدمك تحت تأثير الحريق المباشر. تمت الدراسة على خرسانة ذات مقاومة ضغط ١٣٠ ميجابسكال. وتمت الدراسة على ستة كمرات من الخرسانة المسلحة عالية الاداء وذاتية الدمك تمثل كمرتين منهم خرسانة عالية الآداء ذاتية الدمك بدون الياف وكمرتين خرسانة عالية الآداء ذاتية الدمك فى وجود الياف حديدية والكمرتين الأخريين تمثلان خرسانة عالية الآداء وذاتية الدمك فى وجود ثلاث انواع من الألياف (حديدية وميكروبولى بروبلين وبولى اوليفين). وتم اختبار ثلاث كمرات من الكمرات الستة عند درجة حرارة الغرفة بدون التعرض للحريق والثلاث الكمرات المناظرة تم تعريضها للحريق لمدة ١,٥ ساعة وهى محملة بحمل يساوى ٤٥% من اقصى حمل للكمرة المناظرة والمختبرة عند درجة حرارة الغرفة. وقد تم اختبار جميع الكمرات عن طريق التحميل بحمل مركز فى منتصف بحر الكمرة. وقد اوضحت النتائج الدور المتميز لأستخدام كوكتيل من الألياف وذلك فى تحسين كفاءة الكمرات الخرسانية فى الأنحناء وتقليل تقشر الغطاء الخرسانى عند التعرض للحريق المباشر.

Keywords: High performance concrete; Self compacting concrete; RC beams; Fire; Hybrid fibers; Steel fibers1

1. INTRODUCTION

Reinforced concrete beams function as critical load bearing structural members in a building, and hence the provision of appropriate fire resistance is one of the major design requirements in buildings. The basis for this requirement can be attributed to the fact that when fire suppression and control systems fail, structural integrity is the last line of defense. Fire impacts reinforced concrete members by raising the temperature of the concrete mass. This rise in temperature dramatically reduces the mechanical properties of concrete and steel. Moreover, fire temperatures induce new strains, thermal, and transient creep [1]. They might also result in explosive spalling of surface pieces of concrete members [2]. In previous studies, considerable evidence has emerged which shows that spalling of concrete in accidental fires causes severe damage to concrete members [3-5], especially for high-strength concrete (HSC) and normal strength concrete (NSC) with higher moisture content. In most cases spalling seems to be due to a combination of pore pressure generated by boiling of the free water content, and thermal stresses due to extreme temperature gradients. It can be affected by a number of influences such as temperature gradient, internal thermal micro- cracking, cracking around reinforcement bars and strength loss due to chemical transitions [6,7]. HSC is believed to be more susceptible to this pore pressure build up because of its low permeability compared to NSC. The extremely high water vapor pressure, generated during exposure to fire, cannot escape due to the high density of HSC and this pressure can reach the saturation vapor pressure [8]. At 300 °C, the pore pressure often reaches about 8 MPa. Such internal pressures are too high to be resisted by HSC having a tensile strength of about 5 MPa [9].

High-performance concrete (HPC) has become an attractive option to NSC. HPC is a specialized concrete designed to provide several benefits in the construction of concrete structures. HPC offers high strength, better durability properties, and good construction. High strength is one of the important attributes of HPC. The HPC offers significant economic and architectural advantages over NSC in the correct situations, and is suited well for constructions that require high durability. High-performance concretes having strength in excess of 70 MPa are often used in a wide range of applications. Although HPC has been shown to have a number of advantages when used in concrete structures, it suffers from one major weakness: higher brittleness. When exposed to high temperatures, HPC exhibits more serious degradation than normal concretes do, such as spalling and cracking [10]. Fibers have extensively been used to improve the ductility of concrete. Recently, it has been found that a number of fibers can also improve the residual properties of concrete after exposure to elevated temperatures. Polypropylene (PP) fibers and steel fibers (SF) have been used to reduce spalling and cracking and to enhance the residual strength [11-14]. The primary objective of the present work is to investigate the flexural behavior of RC beams fabricated from HPSCC under direct fire, highlighting the effect of incorporating single or hybrid fibers to the concrete mix.

2. EXPERIMENTAL PROGRAM

All materials used in the present work are locally available materials except SF and PP. Type I ordinary Portland cement was used. Quartz fine sand with maximum nominal size of 0.6 mm was used as aggregate. High ratio of silica fume was used to produce HPSCC [15]. Silica flour is a quartz powder from pure sand. This silica flower was ground to a very fine powder with a diameter ranging from 0.125 to 1.00 μm and used as micro filler to optimize the packing density of the powder mixture. The length and aspect ratio were 60 mm and 67 for the SF, 12 mm and 667 for the micro-PP and 25 mm and 65.8 for the polyolefin (PO) fibers. The used Super-plasticizer was Glenium110M from BASF Company, which complies with ASTM C494 Types B. The water used in this study was clean potable water free from impurities and organic matters. These materials were used to make three HPSCC mixes. The first mix, Mix I, was without fibers, while the second mix, Mix II, was with SF and the third mix, Mix III, was with the three types of fibers (micro-PP, PO and SF). The materials required to produce one cubic meter from each mix are given in Table 1. Slump flow test was carried out according to ASTM C 1611 to measure the fresh properties of the three HPSCC mixes and the results are given in Table 2. The average compressive strength of the three mixes measured was 130 MPa.

Table 1, Mix proportions for producing one cubic meter

Materials		Quantities		
		Mix I	Mix II	MixIII
Cement (kg)		700	700	700
Silica Fume (kg)		203	203	203
Sand (kg)		1080	1080	1080
Silica Flour (Kg)	20 μm	90	90	90
	75 μm	90	90	90
Super Plasticizer (lit)		38	38	38
Water (lit)		161	161	161
Dramix Steel Fiber RC-65/60BN		-	1.3%	1.3%
Micro-polypropylene fiber		-	-	0.13%
Polyolefin		-	-	0.6%
Silica fume/Cement (S/C)		29 %		
Water/Cement (w/c)		0.23		
Water/Binder		18 %		

Table 2, Slump flow values

Mix	Slump flow diameter,mm	T_{50}, sec
Mix I	770	3.9
Mix II	760	4.0
Mix III	725	4.3

To investigate the flexural behavior of RC beams fabricated from the previous mixes, six beams were cast, two from each mix. The beam dimensions were 2500 mm total span, 2300 mm loaded span and 200×200 mm cross section dimensions. Each beam was reinforced by 2Φ14 mm as top reinforcement and 3Φ14 mm as bottom reinforcement. The stirrups were 5Φ8 mm/m. The fabricated beams were de-molded 24 hrs after casting and cured in water for 28 days. The beams were tested under 3-points bending configuration. One from the two was tested to failure at room temperature (RT), while the other was loaded by 45% from the RT fracture load, RTFL, of the corresponding beam and then subjected to direct fire under this sustained load. The beams fabricated from Mix I was denoted as BI, while those fabricated from Mix II and Mix III were denoted as BII and BIII respectively. A custom-built gas furnace was used to expose the RC beams to fire as shown in Fig. 1. The heating arrangement in the furnace is as according to ASTM E 119-00 specifications. The load was applied through pressure valve of 400 bar calibrated with handle jack by (NATIONAL INSTITUTE FOR STANDARD NIS). Deflection gauge with 35mm travel fixed in the jack body was used to measure the deflection until 45% from the fracture load.

Steel rule with 0.5 mm accuracy was fixed in the steel frame beyond an indicator welded in the body of the jack to record the vertical movement of the jacks, beam deflection. High resolution digital camera 30X zooming and 3 hours recording time fixed on a surveying tripod was used to adjust the level. This camera was placed perpendicular to the steel rule and indictor. Three pipes were used to ensure that the fire is uniformly distributed with the same degree of temperature on the three sides of the beams through 30 nozzles for each pipe. Each pipe was connected to a gas cylinder with a safety regulator valve.

3. RESULTS AND DISCUSSION

3.1 Load Deflection Behavior at Room Temperature

Typical load-deflection curves for the three tested beams, BI, BII and BIII, tested at RT are shown in Fig. 2. These curves illustrate typical load-deflection behavior of RC beams. The recorded ultimate loads, Pult, for the three beams are 61, 74, 79 kN respectively for BI, BII and BIII. The addition of SF to HPSCC, B II, leads to an increase by about 21% and 4 % in the ultimate load and corresponding deflection, δ_{ult}, compared to BI as shown in Fig. 3. These ratios increase to 30% and 12% when using hybrid fibers, BIII. These results show the effectiveness of hybrid fibers reinforcement in high strength concrete mixture in increasing the flexural strength and toughness of concrete by preventing the crack development.

3.2 RC Beams under Direct Fire

This study is focusing on the visual inspection of the RC beams exposed to fire. The time to reach failure is defined as the fire resistance for the beam.
A comparison of fire resistance of the three beams given in Table 4 indicates that spalling sounds are started inside the furnace after 15 min from the ignition of fire for beams BI at 690 ºC, while started after 20 and 28 min at 740 ºC and 778 ºC for BII and BIII respectively. Also, beam BI failed before reaching the target time of 1.5 hrs, while BII and BIII succeeded to stay without failure and to resist extra loads in the addition to the 45% RTFL before fracture Examination of photos 1 and 2 clearly indicate the occurrence of sever spalling in beam BI. The spalling length was observed over most of the span of this beam. The spalled length reduced markedly to cover small portion at the beam mid-span with the utilization of hybrid fibers as in the case of BIII.

Photo 3 shows a schematic for the spalled area in the HPSSC beams cross section, with and without fibers after fire exposure. It can be seen that the extent of spalling (ratio of area of spalled concrete to the original area of the concrete cross section) decreases with adding fibers. These observations can lead to the fact that once first spalling occurs, the pore pressure

will build up subsequently in the inner layers of concrete leading to further spalling in the beam. Improvement in spalling resistance was attained by adding steel and PP fibers to the HPSCC concrete mix. Further, spalling, which results in a decrease in the cross-section at later stages of fire exposure, contributed to lowering the fire resistance of the HPSCC beams. Referring to the results recorded for the deflection in RC beams given in Table 5 and Fig. 4, the following observations can be recorded: Beam BI failed before reaching the desired target test time of 1.5 hr. It failed after 76 min from the start of fire. The corresponding recorded deflection is 128 mm. Beams BII and BIII succeeded to reach the target test time (1.5 hrs). After fire switch of, the total deflections caused by fire are found be 123 and 103 mm for BII and BIII respectively. In the addition to the existing load (45% RTFL), extra loads are applied to beams BII and BIII until the hydraulic jack, could no longer maintain the load. These extra loads were 6.7 and 10.4 kN respectively for BII and BIII.

These extra loads caused additional deflections in the two beams equal to 22 mm and 46 mm for BII and BIII respectively. The accumulative deflections corresponding to the ultimate loads recorded for the two beams became 145 and 149 mm for BII and BIII respectively. By comparing results found in Fig. 2 and Fig. 4, it can be observed that: at the moment the hydraulic jack, could no longer maintain the 45% pre-load ratio, the deflection recorded in beam BI after 76 minutes from fire exposure is 128 mm. This deflection is equivalent to a deflection recorded at a load equals 99% of the RTFL for the beam tested without exposure to fire. This means that exposing beams without fibers, BI, for 76 minutes lost its ability to resist 45% RTFL or on other meaning exposing normal concrete beams without fibers for

76 minutes generates stresses equivalent to those generates under 55% from RTFL. The deflection takes place in beam BII (with steel fibers), when loaded by 45% RTFL during exposure to fire for 90 minutes is equivalent to a deflection recorded at a load equals 95% of the RTFL for the corresponding beam tested without exposure to fire. Despite the beams attained these values of deflections, the presence of steel fibers make the beam able to carry extra load of 9 % from RTFL before failure. Beam made with hybrid fibers, beam BIII, shows the same performance as BII with noticeable changes in values. Deflection after exposure to fire for 90 minutes decreased and became equivalent to a deflection recorded at a load equals 90% of the RTFL for the corresponding beam tested without exposure to fire. The ability of beam BIII to carry additional load after exposure to fire increased to 13%.

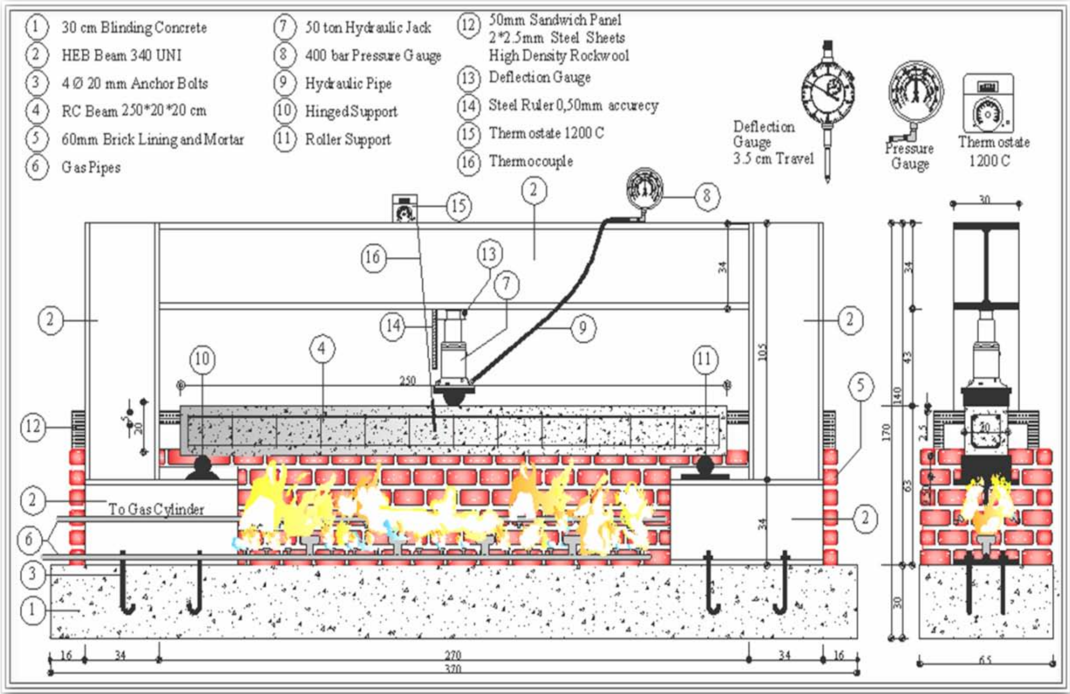


Fig. 1 Test setup for RC beams under gas furnace

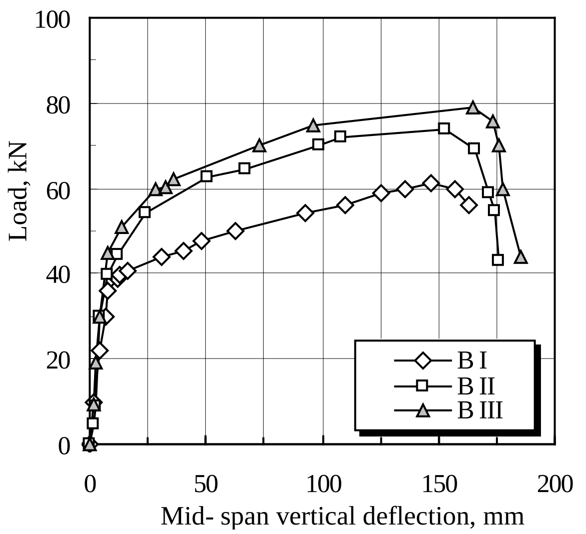


Fig. 2 Load–deflection curves RC beams tested at RT

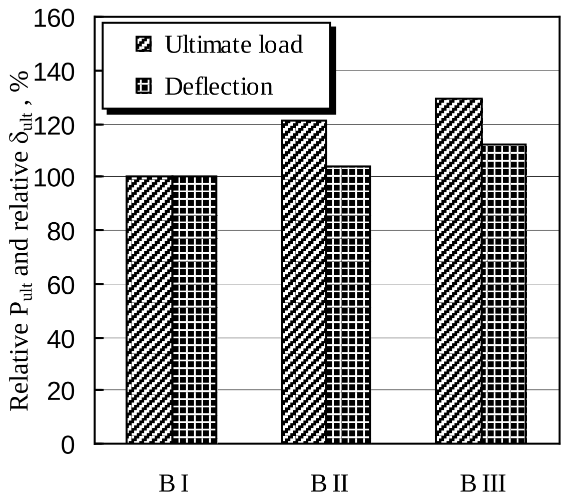


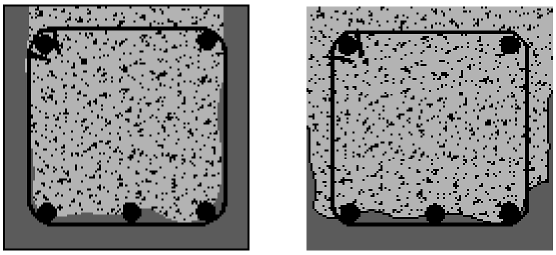
Fig. 3 Relative ultimate loads and corresponding relative deflection for RC beams at RT

Table 4, Beams observation during exposing fire

Beam	45% RTFL, kN	Sound of Spalling				Test Discontinued (failure time, min)
		Start		End		
		Time, min	Temp.,^{o}C	Time, min	Temp.,^{o}C	
BI	27.5	15	690	45	840	76
BII	33.3	20	740	62	867	90 (not failed)
BIII	35.6	28	778	75	875	90 (not failed)

Photo 1 Normal HPSCC beam, BI, after exposing to fire

Photo 2 HPSCC beam, BIII, after exposing fire



HPSCC cross section Without fibers

HPSCC cross section With fibers

Photo 3 Spalling in HPSCC beams cross section exposed to fire

Table 5, Beam deflections due to fire and extra loads

Beam	In fire		After fire		Total accumulative deflection corresponding to ultimate load, mm
	Time, min	Deflection, mm	Extra load, kN	Extra deflection due to load, mm	
BI	76	128	0		128
BII	90	123	6.7	22	145
BIII	90	103	10.4	46	149

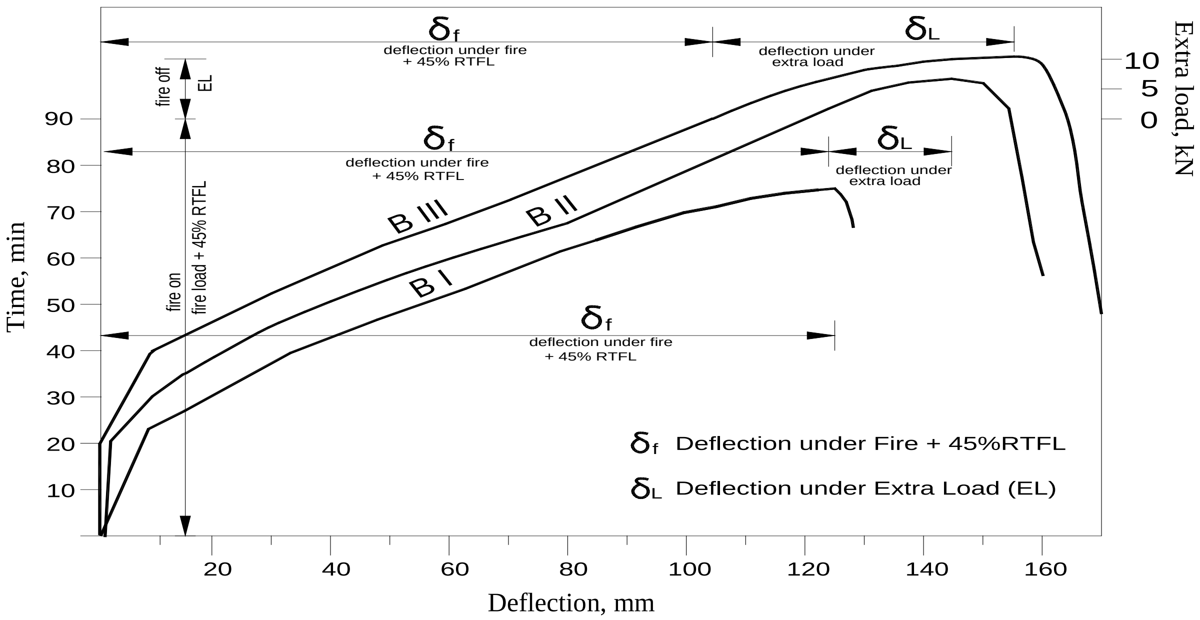


Fig. 4 Time-deflection curves for different RC beams

4. CONCLUSIONS

The results of the present experimental work support the following conclusions:

1. For RC beams tested at RT, the addition of steel fibers to HPSCC, caused an increase by about 21% and 4 % in the ultimate load and corresponding deflection, while these ratios increased to 30% and 12 % when using hybrid fibers from steel and polypropylene (micro-polypropylene and Polyolefin).
2. RC beams from HPSCC without fibers and load by about 45% from the fracture load of the corresponding beam test at RT failed to stay under direct fire for more than 76 min.
3. The addition of fibers, either single or hybrid, to HPSCC make the RC beams to stay under direct fire for 90 min without failure and cause a reduction in the measured deflection and increase the ability of these beams to sustain an extra load before failure.
4. Sever cover spalling occurred all over the span of HPSCC beams without fibers, while the addition of fibers reduced the spalling to a very limited length over the beam span. This can explain the un-ability of beam without fibers to maintain carrying the preload during exposure to fire and why this beam has the shortest life time among the other beams incorporating fibers.
5.

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