COMPARATIVE FIRE PERFORMANCE OF HIGH STRENGTH CONCRETE COLUMNS WITH DIFFERENT TYPES OF FIBER REINFORCEMENT

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Abstract

Reinforced concrete (RC) columns made of high strength concrete (HSC) experience faster degradation of capacity and spalling when exposed to fire. To mitigate such fire induced spalling and enhance fire resistance, fibers are often added to HSC mix. This paper presents results from fire resistance tests to illustrate the comparative fire performance of HSC columns with different fiber combinations. Four reinforced concrete (RC) columns made of HSC with plain, polypropylene, steel, and hybrid fibers were tested under design fire conditions and data from tests is utilized to evaluate the comparative fire behaviour of these columns. Results from these fire resistance experiments show that hybrid fiber reinforced HSC columns exhibit improved performance as compared to plain, polypropylene, and steel fiber reinforced columns.

Keywords: fire response, high strength concrete columns, polypropylene fibers, steel fibers, hybrid fibers, spalling

INTRODUCTION

Fire represents one of the most severe environmental conditions to which structures may be subjected, and hence, provision of appropriate fire safety measures is an important aspect in high rise buildings. In recent years there is an increased use of high strength concrete (HSC) for structural members in buildings. However, various studies show that HSC columns exhibit lower fire resistance than that of normal strength concrete (NSC) columns (Ali, Nadjaiet al., 2004, Kodur, Chenget al., 2003, Kodur and McGrath, 2003). The lower fire resistance of HSC columns is attributed to faster degradation of strength of HSC with temperature and occurrence of fire induced spalling(Diederichs and Schneider, 1995, Kodur, Chenget al., 2003, Hertz, 2003).

Fire induced spalling is attributed to dense microstructure and lower permeability of HSC that prevents dissipation of pore pressure generated from water vapor in HSC members when exposed to high temperatures(Kodur and Dwaikat, 2008). When this pore pressure build-up exceeds the tensile strength of concrete, pieces of concrete break-off from the surface of concrete structural member(Kodur and Dwaikat, 2008). With increasing temperature, tensile strength of concrete also decreases and thus the risk of spalling increases. The faster degradation of compressive strength with temperature, combined with occurrence of spalling, leads to lower fire resistance in HSC members.

To mitigate fire induced spalling in HSC members, researchers have recommended the addition of polypropylene fibers to concrete (Ali, Nadjaiet al., 2004, Kodur, 2000, Kodur and Phan, 2007). These polypropylene fibers melt at relatively low temperatures (about 167-170°C) and create randomly oriented micro and macro channels inside concrete. These channels facilitate dissipation of high vapor pressure generated in concrete members. Another approach to overcome spalling is through enhancing tensile strength of concrete which is facilitated through adding steel fibers(Kodur, 1999). Alternatively, hybrid fibers comprising of both polypropylene and steel fibers can be added to HSC to mitigate fire induced spalling in HSC members (Ali and Nadjai, 2008).There have been numerous studies on fire performance of HSC columns with polypropylene fibers, but there are only limited studies on fire performance of HSC columns with steel and hybrid fiber reinforcement. Further there is lack of information on comparative fire performance of HSC columns made with different fibers.

To illustrate comparative fire performance of HSC columns with different fiber combinations, fire resistance tests were carried out on HSC columns with different fiber reinforced concrete mixes. Data generated in fire resistance tests is utilized to discuss the effect of different fiber combinations on fire performance of HSC columns.

2 EXPERIMENTAL PROGRAM

To generate data on HSC columns with different fiber combinations, fire resistance experiments were carried out on four HSC columns fabricated with plain, polypropylene fiber, steel fiber and hybrid fiber reinforced high strength concrete.

2.1 Mix Proportions and Column Characteristics

The experimental program consisted of conducting fire resistance tests on four reinforced concrete columns designated as HSC (plain – without fibers), HSC-P (with polypropylene fibers), HSC-S (with steel fibers) and HSC-H (with hybrid fibers). All four columns were 3300 mm long and were of square cross section of 203×203 mm. The columns had four 19 mm dia bars as longitudinal reinforcement and 10 mm ties, at 200 mm spacing, as transverse reinforcement. The steel of main reinforcing bars and stirrups had specified yield strength of 420 MPa. Steel plates of size 406×406×25 mm were attached to the top and the bottom of the column in order to fix the column in position and for facilitating load transfer from the actuator. The actual support conditions of columns were close to partially fixed, however pin-pin end condition were assumed for conservative load calculations.

The size of the test columns was dictated by dimensions of furnace and loading equipment and thus the columns had to be designed as slender (with slenderness ratio 61) as per ACI 318 specifications(2011). As per ACI 216.1 (2007) specifications, these columns were designed for two hour fire resistance rating. A summary of column characteristics, test parameters and results from fire resistance tests on these columns is tabulated in Tab. 1.

Tab. 1 Summary of column characterises, test parameters and results

Column designation	Fire exposure (ASTM E119 – decay)	Total test duration (minutes)	Concrete strength (MPa)		Column capacity (kN)	Load ratio (%)	Applied load (kN)	Relative humidity (%)	Failure time (minutes)	Extent of Spalling (% exposed volume)
			28 Day	Test day						
HSC	SF- decay @8°C/min	180	91	107	1260	60	760	86.6	75	Severe (40)
HSC-P	LF- decay @11°C/min	270	85	93	1260	60	760	92.5	221	Minor (10)
HSC-S	LF- decay @11°C/min	270	72	77	1060	60	640	91.25	No Failure	Nil (0)
HSC-H	LF- decay @11°C/min	270	75	80	1100	60	660	89.65	No Failure	Nil (0)

The columns were fabricated from four batches of HSC mix, one with no fibers and the other three columns with different fiber types. For fiber reinforced HSC mixes, commercially available fibers, NOVOCON XR type steel fibers and MONOFILAMENT (multi-plus) polypropylene fibers were added. Steel fibers were 38 mm in length and 1.14 mm equivalent diameter and had a specified tensile strength of 966 MPa. Polypropylene fibers in HSC-P and HSC-H batch mix were of nonabsorbent type with 20 mm length, 0.91 specific gravity and 162°C melting point. Steel fibers in HSC-Sand HSC-H mix comprised of 42 kg/m^3 of

concrete representing 0.54% by volume. In HSC-P and HSC-H mix, polypropylene fibers weighing 1 kg/m^{3}of concrete representing 0.11% by volume were added.
The columns were cast horizontally and were moist cured in the forms for 7 days. Then the specimens were lifted from the forms and stored at ambient conditions, maintained at about 25°C and 40% relative humidity. Three cylinders from each concrete batch mix were tested to evaluate compressive strength at 7, 28 and 90 days respectively. The average compressive strength of concrete measured on 100×200 mm cylinders at 28 days ranged from 72-91 MPa and is given in Table 1. Just prior to undertaking fire tests, the room temperature moisture conditions (relative humidity) and compressive strength of concrete were also measured and this is also given in Tab. 1.

2.2 Instrumentation

The instrumentation in the test columns included thermocouples (TC), strain gauges (SG), and linear position transducers (LPT). Thirteen type-K (Chromel-alumel) thermocouples of 0.91 mm thickness were installed in columns for measuring concrete and rebar temperatures. Also strain gaugeswere mounted on three main longitudinalrebars. The location and numbering of thermocouples and strain gauges in the cross-section are shown in Fig. 1. The lateral deformations were also measured by placing two LPTs outside of furnace attached to columns with chromelwires.

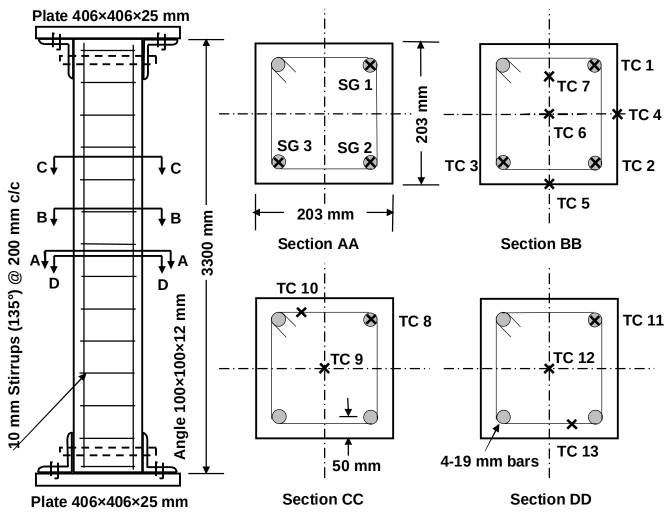


Fig. 1 Column dimensions and location of thermocouples (TC) and strain gauges (SG)

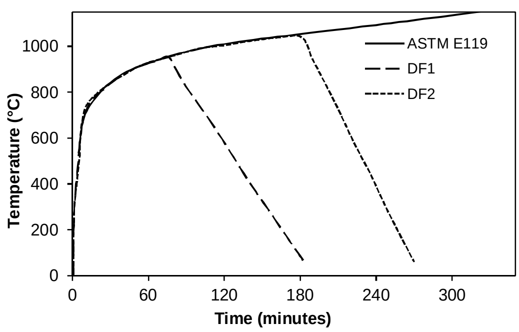


Fig. 2 Fire scenarios and furnace

2.3 Test Conditions and Procedure

The fire resistance tests were carried in the structural fire test furnace at Michigan State University (MSU). The test furnace has been specially designed to produce conditions, such as temperature, loads and heat transfer, to which a structural member might be exposed during a fire. The furnacehas the capacity to supply both heat and applied loads that are present in a typical structural member exposed to fire.The furnace accommodates two columns at a time and different load level can be applied on each column. Full details onthe furnace are given by Kodur and Fike (2009).
The fire resistance tests were carried out by exposing middle 1.68 m of the 3.3 m high columns from all four sides. HSC column without fibers was exposed to ASTM E119 (2008) standard fire exposure (DF1) for 90 minutes followed by a decay phase (8°C/min) as shown in Fig. 2. HSC-P, HSC-S, and HSC-H columns were tested under a parametric (design) fire exposure, comprised of a growth phase as per ASTM E119 (2008) standard fire exposure (DF2) for 3 hours, followed by a decay phase (11°C/min) as shown in Fig. 2. The well-

defined decay (cooling) phase was obtained by controlling temperatures to decay at a predetermined cooling rate (DF1 or DF2), to represent typical fire in a building.
All four columns were tested under a concentric axial load equivalent to 60% (load ratio)of the capacity of the column. The load ratio is the ratio of the applied (test) load to the column capacity at ambient conditions, computed according to ACI 318 (2011). The load was applied approximately 30 minutes before the start of the fire resistance test and was maintained until the column failed under fire exposure. During the test, the columns were exposed to heat controlled in such a way that the average temperature in the furnace followed, as closely as possible, the parametric fire curve. The load was maintained constant throughout the fire test duration. The columns were considered to have failed when the actuator could no longer maintain the load.

3 RESULTS AND DISCUSSION

A summary of results of fire resistance tests onfour columns (HSC, HSC-P, HSC-S, and HSC-H) is tabulated in Table 1. The fire performance of these columns is evaluated in the form of thermal response, structural response, spalling progression and failure times.

3.1 Thermal Response

The thermal response of all four columns is shown in Fig. 3 by plotting comparative temperatures profiles in rebar, and concrete (at mid depth) as a function of fire exposure time. In all columns, an initial plateau can be seen in rebar and concrete temperatures around 100°C and this can be attributed to heat from fire being utilized for evaporation of free water in concrete. After this initial plateau, the temperatures in concrete and rebars increase with fire exposure time. It can be noted that, in all four columns, the progression of temperatures in concrete (at mid-depth) is lower than that in rebars. This can be attributed to lower thermal conductivity and higher specific heat of concrete which delays temperature rise to inner layers of concrete.

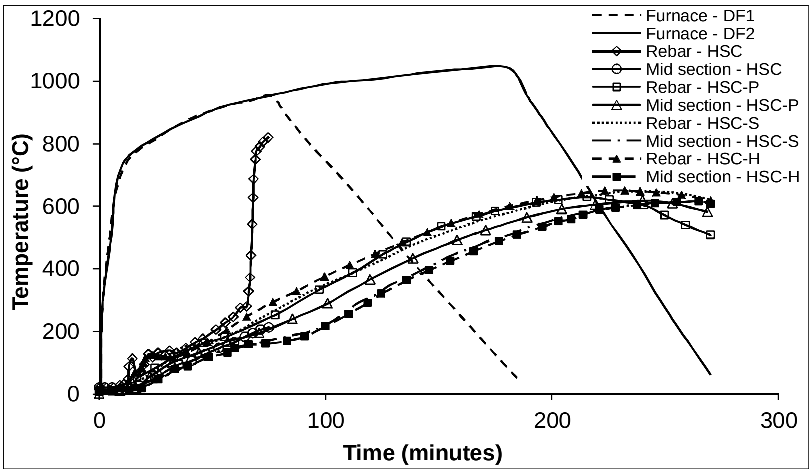


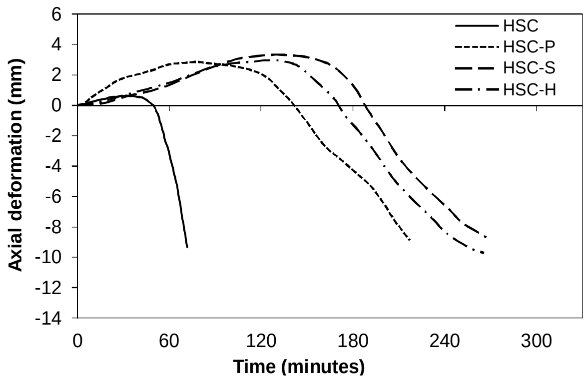
Fig. 3 Comparative temperature progression in HSC columns with different fibers

In HSC column without any fibers, severe spalling occurred which led to loss of concrete cross-section. This loss of concrete resulted in rapid rise of temperatures in rebars as shown in Fig 3. The spalling and loss of concrete cross-section in HSC column can be attributed to pore pressure build-up resulting from lower porosity in HSC.
HSC column with polypropylene fibers experienced some level of surface scaling and resulted in minor loss of concrete cross-section that led to slightly faster rise in temperatures in HSC-P column as seen in Fig. 3. The temperature progression in both HSC-S and HSC-H columns follow similar trends to that of HSC-P column, however HSC-P column experienced

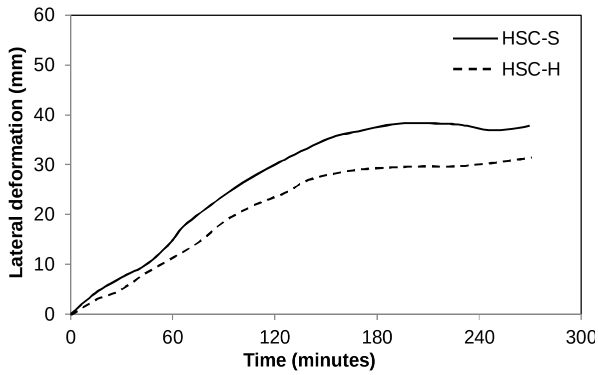
lower temperature rise both in rebars and concrete at mid-section. The higher temperature in HSC-P can be attributed to slightly higher thermal conductivity and specific heat of HSC with polypropylene fibers (Kodur and Khaliq, 2011).

3.2 Structural Response

Structural response of concrete column scan be assessed by monitoring axial and lateral deformations in columns. Only axial deformations were measured in the first two tests on HSC and HSC-P columns due to lack of expertise initially for measuring lateral deformations. However, both axial and lateral deformations were recorded in the case of HSC-Sand HSC-H columns. The structural response of four columns is evaluated by comparing measured axial deformations as a function of fire exposure time, which is shown in Fig. 4.



(a) axial deformations



(b) lateral deformations

Fig. 4 Comparative structural response in HSC columns with different fiber combinations

A reinforced concrete column, when exposed to fire, expands initially due to thermal expansion occurring both in steel rebars and in concrete. With increasing fire exposure time, strength loss occurs in both steel and concrete (Kodur and McGrath, 2003). With further increase in temperature, the loss of strength and stiffness properties in concrete lead to increased load induced mechanical strains which in turn results in significant contraction of the columns.

The axial deformation of the columns plotted in Fig 4(a) illustrates that all four columns exhibit initial expansion phase followed by contraction with increasing fire exposure time. It can be noted that HSC column without fibers had earliest onset of axial deformation and failed through excessive contraction in about 75 minutes. This can be attributed to capacity degradation that resulted from loss of concrete cross-section due to severe spalling (Raut and Kodur 2010). HSC column with polypropylene fibers also endured axial deformation sand failed in about 221 minutes. The axial deformations in HSC-P column was not abrupt as in the case of HSC column without fibers. This can be attributed to spalling mitigation facilitated by melting of polypropylene fibers present in concrete. The overall progression of axial deformation in both HSC-S and HSC-H columns was similar to that in HSC-P column. The onset of both expansion and contraction in these columns was slower which can be attributed to slow degradation of compressive and tensile strength in HSC-S and HSC-H columns facilitated by presence of steel fibers(Khaliq and Kodur, 2011, Lie and Kodur 1996). Also, no fire induced spalling was observed in HSC-S and HSC-H columns, and this in turn led to better fire performance in these columns as compared to that in HSC and HSC-P columns.

Fig. 4(b) illustrates the progression of lateral deformation in HSC-S and HSC-H columns as a function of fire exposure time. The lateral deformation in these columns increased gradually and reached to a maximum of 35 to 40 mm in about 150-180 minutes of fire exposure time. The lateral deformations then remained almost constant till the end of the test. This constant lateral deformation in HSC-S and HSC-H columns can be attributed to slower degradation of strength and no loss of concrete cross-section due to absence of fire induced spalling.

3.3 Fire Induced Spalling

The progression and extent of spalling in tested columns was recorded qualitatively through visual observations during fire tests and was also evaluated by measuring the volumetric loss of concrete in fire exposed columns after fire tests and this is tabulated in Tab. 1. Fig. 5 shows pictures of all four columns after fire resistance test.

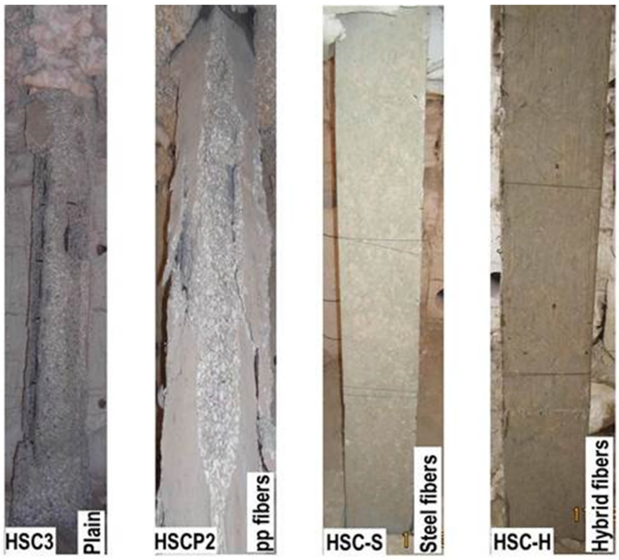


Fig. 5 State of high strength concrete columns after the fire resistance tests

Significant spalling occurred in HSC column without fiber sand this can be attributed to higher compactness and lower permeability of high strength concrete which results in the pore pressure build-up within the cross section. When this pore pressure exceeds the tensile strength of concrete, chunks of concrete break-off from the surface(Bilodeau, Koduret al., 2004, Dwaikat and Kodur, 2010). Reduced spalling in HSC-P column can be attributed to presence of polypropylene fibers. These polypropylene fibers melt at about 160°C and create micro channels in concrete that help to diffuse pore pressure build-up and thus reduce spalling (Kodur, 2000).No fire induced spalling was observed in HSC-S and HSC-H columns. This can be attributed to increased tensile strength facilitated by the presence of steel fibers in HSC-S and HSC-Hand also increased permeability achieved through melting of polypropylene fibers in the case of HSC-H column (Khaliq and Kodur, 2011).

4 FIRE RESISTANCE

A comparison of fire resistance of four columns is given in Table 1.The time to reach failure is defined as the fire resistance and failure is said to occur when the strength of the column decreases to a level at which the column cannot sustain the applied load. HSC column without fibers failed only 75 minutes while HSC-P column failed in 221 minutes. This shows that significant increase in fire resistance of HSC columns can be achieved through adding polypropylene fibers to concrete mix.

In the case of HSC-S and HSC-H columns, fire induced spalling was not encountered and consequently these columns did not fail and survived burnout conditions. The steel fibers in HSC-S, and HSC-H columns helped to slowdown degradation of compressive and tensile strength of concrete and polypropylene fibers in HSC-P column mitigated spalling. The higher fire resistance in HSC-S and HSC-H columns can therefore be attributed to presence of steel and hybrid fibers respectively.

5 SUMMARY

Results from fire resistance tests clearly show that fiber reinforced HSC columns exhibit improved fire resistance as compared to HSC column without fibers. The fire resistance of plain HSC column was significantly lower due to the occurrence of fire induced spalling. Presence of polypropylene fibers in HSC-P column, help mitigate fire induced spalling by relieving the pore pressure and enhance its fire resistance. Presence of steel fibers in both HSC-S column help enhance tensile strength of HSC at elevated temperatures and thus minimize spalling and enhance fire performance. Presence of hybrid fibers in HSC-S column not only benefits from improved tensile strength (through steel fibers), but also through higher permeability in concrete (through polypropylene fibers) and this leads to significant increase in fire performance. Thus HSC columns with hybrid fibers exhibit superior performance under fire conditions.

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