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Effect of silica fume and lateral confinement on fire endurance of high strength concrete columns

V.K.R. Kodur and R. McGrath

Abstract: Fire represents one of the most severe environmental conditions, and therefore should be properly accounted for in the design of structural members. The increased use of high strength concrete (HSC) in buildings has raised concerns regarding the behaviour of such concrete in fire. In particular, spalling at elevated temperatures, as identified in studies by a number of laboratories, is a main concern. In this paper, results from experimental studies on the fire resistance of HSC columns are presented. A comparison is made of the fire resistance performance of HSC columns with and without silica fume and with different confinement configurations. The effect of silica fume and the effect of confinement on the fire performance of HSC columns will be discussed. The results show that the fire endurance of HSC columns with higher silica fume content is lower and the reduced tie spacing and the provision of cross-ties are beneficial in minimizing the spalling in HSC.

Key words: fire resistance, high strength concrete, reinforced concrete columns, spalling.

Résumé : Le feu représente l'une des conditions environnementales les plus graves et il faudrait donc en tenir compte adéquatement lors de la conception des éléments de charpente. L'utilisation accrue de béton à haute résistance dans les bâtiments a soulevé des inquiétudes concernant le comportement d'un tel béton lors d'un incendie. Plus particulièrement, l'effritement à des températures élevées, tel qu'il a été identifié dans de nombreuses études de laboratoire, est la préoccupation principale. Le présent article présente les résultats d'études expérimentales sur la résistance au feu des colonnes en béton à haute résistance. Le rendement de résistance au feu des colonnes en béton à haute résistance avec et sans fumées de silice est comparé à diverses configurations de confinement. L'effet des fumées de silice et l'effet du confinement sur le rendement des colonnes en béton à haute résistance contre le feu sont examinés. Les résultats montrent que la résistance au feu des colonnes en béton à haute résistance avec des teneurs supérieures de fumées de silice est moindre et la réduction de l'espace entre les barres ainsi que l'apport de ventrières minimisent l'effritement du béton à haute résistance.

Mots clés : résistance au feu, béton à haute résistance, colonnes en béton armé, effritement.

[Traduit par la Rédaction]

Introduction

In recent years, the construction industry has shown significant interest in the use of high-strength concrete (HSC). This is because of the improvements in structural performance, such as high strength and durability, of HSC as compared with traditional normal strength concrete (NSC). The use of HSC, which was previously limited to bridges, offshore structures, and infrastructure projects, is becoming

more popular in high-rise buildings. One of the major uses of HSC in buildings is for columns.

Silica fume and other admixtures are often used in the mix design to achieve the high strength in concrete. The increased use of HSC has raised concerns regarding the behaviour of such concretes in fire. In particular, the occurrence of spalling (often explosive) at elevated temperatures, when HSC is subjected to rapid heating, as in the case of a fire, is one of the reasons for this concern (Kodur 2000). Further, results of fire tests in a number of laboratories (Phan 1996; Diederichs et al. 1995; Kodur and McGrath 2003; Hertz 2003; Phan and Carino 2002) have shown that there are well-defined differences between the properties of HSC and NSC at elevated temperatures.

Provision of appropriate fire endurance to columns is one of the primary design requirement in building design, since columns are the primary load bearing members. The specifications for fire resistance of structural members are contained in the National Building Code of Canada (NBCC 1995). Concrete structures in Canada are to be designed in accordance with the CSA A23.3-M94 standard (CSA 1994). The most recent edition of this standard contains detailed specifications on the design of HSC structural members; however, there are no guidelines for the fire resistance de-

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Written discussion of this article is welcomed and will be received by the Editor until 30 June 2006.

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sign of HSC structural members either in CSA A23.3-M94 (CSA 1994) or the NBCC (1995).

Recently National Research Council Canada (NRC), in collaboration with the Portland Cement Association (PCA) and the Cement Association of Canada (CAC), has completed a major research study to examine the behaviour of HSC columns. The main objective of this study was to investigate the influence of silica fume, to determine confinement on fire performance of HSC columns, and to evaluate fire endurance of HSC. As part of this research, fire endurance experiments on full scale HSC columns were carried out. In this paper a comparison is made of the fire resistance performance of HSC columns with and without silica fume and with different confinement configurations. The effect of silica fume and the effect of confinement on the fire performance of high strength concrete columns is discussed. Also, the various factors that influence the structural behaviour of HSC columns under fire conditions are outlined.

Concrete under fire

Structural members are to be designed to satisfy the requirements of serviceability and safety limit states for various environmental conditions. Fire represents one of the most severe conditions and hence the provision of appropriate fire safety measures for structural members is a major safety requirement in building design (NBCC 1995). The basis for this requirement can be attributed to the fact that structural integrity is the last line of defence, when other measures for containing the fire fail.

Generally, concrete structural members (traditionally used to be made of NSC) exhibit good performance under fire situations. Studies show, however, that the performance of HSC is different from that of NSC and may not exhibit good performance in fire. Further, the spalling of concrete under fire conditions is one of the major concerns due to the low porosity in HSC. The spalling of concrete exposed to fire has been observed under laboratory and real fire conditions (Kodur 2000; Phan 1996; Phan and Carino 2002). Spalling, which results in the rapid loss of concrete during a fire, exposes deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the inner layers of the member, including the reinforcement.

Spalling is theorized to be caused by the build-up of pore pressure during heating (Kodur 2000; Diederichs et al. 1995; Hertz 2003). The HSC is believed to be more susceptible to this pressure build-up because of its low permeability compared with NSC. The extremely high water vapour pressure, generated during exposure to fire, cannot escape because of the high density of HSC, and this pressure often reaches the saturation vapour pressure. At 300 °C, the pressure reaches about 8 MPa. Such internal pressures are often too high to be resisted by the HSC mix having a tensile strength of about 5 MPa (Diederichs et al. 1995).

Data from various studies (Kodur 2000; Phan 1996; Kodur and McGrath 2003; Phan and Carino 2002) show that the fire behaviour of HSC, in general, and spalling, in particular, is affected by a number of factors. However, there is no data on the effect of silica fume or the effect of cross-ties on the fire endurance of HSC columns. In this paper, the effect of silica

fume and the effect of confinement on the fire performance of high strength concrete columns will be discussed.

Fire endurance experiments

Fabrication of columns

The experimental program consisted of conducting fire resistance tests on six reinforced concrete columns, designated HS2-1 to HS2-6. All six columns were made of HSC and had 3810 mm length and 406 mm square cross-section. The dimensions of the column cross section and other specifics of the columns are given in Table 1.

Deformed bars meeting the requirements of ASTM A615-80 were used for both main longitudinal bars and ties. All reinforcement had a specified yield strength of 400 MPa. The longitudinal reinforcement in all columns was comprised of eight 25 mm (No. 8) bars symmetrically placed with 40 mm clear cover to the tie reinforcement. The main reinforcing bars were welded to steel end plates. The percentage of longitudinal steel in all columns was 2.42%.

The lateral reinforcement consisted of 10 mm (No. 3) ties. The spacing of the ties varied from a maximum dimension of h , to a minimum dimension of $h/2$, where h represents the cross-sectional dimension of the column equal to 406 mm. In columns HS2-1 and HS2-4, the ties were spaced at a distance of $h/2$, while in columns HS2-2 and HS2-5, the spacing was $3h/4$. For columns HS2-3 and HS2-6, the ties were provided at a spacing of h . The location and layout of the ties are shown in Fig. 1. The confinement effect in columns HS2-3 and HS2-6 was enhanced by providing an additional two 10 mm (No. 3) cross-ties (tie configuration #2), as shown in Fig. 1. All ties were lapped with 135° bends at the ends. The clear concrete cover of the ties was 38 or 40 mm in all columns. Full details of ties, including the spacing and configuration, are given in Fig. 1 and Table 2.

Two batches of concrete mixes were used for fabricating the columns to obtain required test variables, such as silica fume, concrete strength, and aggregate type and size. Columns HS2-1 to HS-3 were fabricated from batch 1 mix, while columns HS2-4 to HS-6 were fabricated from batch 2 concrete mix. The two batches of concrete were made at the Construction Technology Laboratories Inc. (CTL) in Skokie, Illinois, USA. Batches 1 and 3 were made with carbonate aggregate, while batch 2 was made with siliceous aggregate.

Both batches of concrete were made with general purpose Type 10 Portland cement. Batch 1 mix was proportioned with carbonate aggregate and no silica fume, while Batch 2 mix was made with 13.3% silica fume and siliceous aggregate mix. The 28 d cylinder compressive strength of concrete batches ranged from 75 to 101 MPa. The corresponding compressive strength on the day of the fire endurance tests ranged from 85 to 113 MPa. Batch quantities and measured properties of the concrete are given in Table 3.

Type-K chromel-alumel thermocouples, 0.91 mm thick, were installed at mid-height in the columns for measuring concrete temperatures at different locations in the cross section. To measure the concrete temperatures, thermocouples were mounted on supplemental support, while steel temperatures were measured by mounting the thermocouples on rebars and ties. Full details on fabrication of these columns

Table 1. Summary of test parameters and results.

Column designation	Concrete strength test day (MPa)	Aggregate type	RH (%)	Pr (f'_c 28 d) (kN)	Test load (kN)	Test load / maximum service load*	Fire endurance (min)
HS2-1	81	C	69.5	5065	3895	0.90	299
HS2-2	81	C	58.0	5065	4328	1.00	343
HS2-3	81	C	61.0	5065	4328	1.00	379
HS2-4	114	S	57.0	6534	4567	0.85	146
HS2-5	114	S	77.0	6534	5373	1.00	108
HS2-6	114	S	98.1	6534	3546	0.66	142

Note: Pr, factored resistance of the column; C, 3/4" carbonate aggregate; S, 3/4" siliceous aggregate; RH, internal relative humidity of the column at the time of the test.

*The maximum service load is determined in accordance with CAN/ULC S101 (ULC 2004) standard method of fire endurance tests of building construction materials. This procedure requires that the service loads, used in the fire test, be calculated back from the factored resistance of the column using the live load to dead load ratio that is assumed applicable to the element being tested. The column tests reported in Table 1 above used various percentages of the full service load as noted.

Fig. 1. Elevation and cross section of reinforced concrete columns. **Table 2.** Extent of spalling in HSC columns.

Column designation	f'_c at time of test (MPa)	Aggregate type	Tie spacing	Test load / max. service load	Fire endurance (min)	Spalling at start	Spalling mid way	Spalling at failure
HS2-1	85	C	H/2	0.90	299	Minimum	None*	Moderate
HS2-2	85	C	3h/4	1.00	343	Minimum	None	Moderate
HS2-3	85	C	h	1.00	379	Minimum	None	Moderate
HS2-4	114	S	H/2	0.85	146	Minimum	Significant	Very significant
HS2-5	114	S	3h/4	1.00	108	Minimum	Significant	Very significant
HS2-6	114	S	h	0.66	142	Minimum	Significant	Very significant

Note: Test load, applied test load; C, carbonate aggregate; S, siliceous aggregate.

*None, no further spalling.

Table 3. Concrete mix batch quantities for columns HS2-1 to HS2-6.

Parameter – (units/m ³)	Unit	Batch 1	Batch 2
Cement type I	kg	341	339
Silica fume ^a	kg	—	56.7
Fly ash class F	kg	74.8	31.8
Coarse aggregate (SSD)	kg	816.5	799.2
Aggregate type ^b		C	S
Aggregate size	mm	19	19
Fine aggregate (natural sand)	kg	471.7	556.1
Water-reducer	L	1.1	2.1
HR WR type F	L	5.7	13.5
Total water ^c	kg	132.4	81.6
Water/cement ratio		0.38	0.24
Water/binder ratio		0.32	0.19
% Silica fume		—	13.3
% Fly ash		18	7.4
Slump	mm	178	216
28 d compressive strength	MPa	75	101

^aDry weight.^bC, carbonate aggregate; S, siliceous aggregate.^cWeight of total water in mix including admixtures.

including rebar arrangement, concrete placement, curing and instrumentation are given by Kodur et al. (2004a, 2004b).

Experimental set-up

The experimental studies were carried out by exposing the columns to heat in a furnace especially built for testing loaded columns. The furnace consists of a steel framework supported by four steel columns, with the furnace chamber inside the framework. The test furnace was designed to produce conditions, such as temperature, structural loads, and heat transfer, to which a concrete member might be exposed during a fire. The furnace has a loading capacity of 1000 t. Full details on the characteristics and instrumentation of the column furnace are provided by Lie (1980).

The columns were installed in the furnace by bolting the endplates to a loading head at the top and to a hydraulic jack at the bottom. All columns were tested with both ends fixed, i.e., restrained against rotation and horizontal translation. For this purpose, eight 19 mm diameter bolts, spaced regularly around the column, were used at each end to bolt the end plate to the loading head at the top and to the hydraulic jack at the bottom. For each column, the length exposed to fire was approximately 3000 mm. At high temperature, the stiffness of the unheated column ends, which is high in comparison to that of the heated portion of the column, contributes to a reduction in the column effective length. In previous studies (Lie and Woollerton 1988), it was found that an effective length of 2000 mm represents experimental behaviour for testing of fixed-end columns.

All columns were tested under a concentric load and the applied load on the columns ranged from 66% to 100% of full service load (factored compressive resistance of the column), determined according to the CSA standard CSA-A23.3-M94 (CSA 1994). The factored compressive resistance of each column as well as the applied loads is given in Table 1. The factored compressive resistance of the columns were calculated using the effective length factor, K , 0.65 for

fixed ends. The factored resistance computed using the PCACOL computer program (CAC 1994), together with applied loads on the column, is given in Table 1. The load intensity, defined as the ratio of the applied load to the full service load, varied slightly to determine the influence of load on fire resistance.

Experimental procedure

Since relative humidity has significant influence on the fire performance of concrete columns, a year or more elapsed between the time a column was fabricated and the time it was tested (Kodur et al. 2004a). The moisture condition in the concrete core of the columns was measured, at about 50.8 mm deep, on the day of the test by inserting a Vaisala moisture sensor into a hole drilled in the concrete. In general, a moisture content, corresponding to approximately 57% to 98% relative humidity, at room temperature, was measured. The relative humidity of each column is given in Table 1.

The load was applied approximately 45 min before the start of the fire test and was maintained until a condition was reached at which no further increase of the axial deformation could be measured. This was selected as the initial condition for the axial deformation of the column. During the test, the column was exposed to heating controlled in such a way that the average temperature in the furnace followed, as closely as possible, the ASTM E119-88 (2001) or CAN/ULC-S101 (ULC 2004) standard temperature–time curve. The load was maintained constant throughout the test. The columns were considered to have failed and the tests were terminated when the hydraulic jack, which has a maximum speed of 76 mm/min, could no longer maintain the load.

The furnace, concrete, and steel temperatures as well as axial deformations of the columns were recorded at 1 min intervals. Also, during fire tests, visual observations were made through window ports to record spalling as well as crack propagation in the columns.

Results and discussion

The results of the six column tests are summarized in Table 1, in which the column characteristics, test conditions, and fire endurance are given for each column. Full results from experiments, including the furnace, concrete, and steel temperatures as well as the axial deformations of the column specimens recorded during the tests, are given by Kodur et al. (2004a).

During the fire endurance tests, special attention was paid to make visual observations and to record spalling as well as crack propagation in the columns. Also, after the completion of fire tests, post-test observations were made to analyse the failure pattern, extent and nature of spalling, and condition of rebars and ties. The following is a discussion based on the recorded results and the observations:

Variation of temperatures

Typical temperature–time values, measured during the test, in the furnace, reinforcement, and at various depths in concrete are plotted in Figs. 2 and 3 for columns HS2-1 and HS2-4, respectively. The measured temperature in the fur-

Fig. 2. Measured temperature distribution in column HS2-1 as a function of time. **Fig. 3.** Measured temperature distribution in column HS2-4 as a function of time.

nace followed closely the ASTM standard temperature–time curve through out the duration of the test. The temperatures inside the tested concrete rose rapidly to about 100 °C and then the rate of increase of temperature decreased. Earlier studies have shown that this temperature behaviour is due to the thermally induced migration of moisture toward the centre of the column (Lie and Celikkol 1991; Kodur et al. 2004b). The influence of moisture migration is highest at the centre of the column. Although there are slight differences in the temperature propagation of the two HSC columns, they follow a similar trend overall. These variations, such as temperatures at 13.4 mm and 204 mm depth in HS2-1 and at 204 mm depth in H2-4, could be attributed to the dislocation of thermocouples during the placement of concrete or to the

movement of thermocouples due to the occurrence of spalling of concrete.

Variation of deformations

The variation in axial deformation with time for column HS2-1 and HS2-4 is shown in Figs. 4 and 5, respectively. The columns expanded until the reinforcement yielded and then contracted leading to failure. The deformation in the columns resulted from several factors, such as load, thermal expansion, and creep. The initial deformation of the column was mainly due to the thermal expansion of concrete and steel. While the effect of load and thermal expansion is significant in the intermediate stages, the effect of creep be-

Fig. 4. Axial deformations in column HS2-1 as a function of time.

Fig. 5. Axial deformations in column HS2-4 as a function of time.

comes pronounced in the later stages because of the high fire temperature.

The expansion range and its magnitude is significantly higher in column HS2-1 than in column HS2-4. This is because the contribution from thermal expansion dominated the deformations as a result of the relatively lower load level in column HS2-1. Further, since there was lesser confinement, column HS2-4 failed in a brittle manner just after reaching the expansion plateau, without undergoing significant contraction. However, in column HS2-1, because of a relatively higher load intensity and higher confinement level,

the load and creep effects contributed significantly to deformations (contractions).

Cracking, spalling pattern, and failure mode

The results of the column tests are reported in Table 1 and are described in detail by Kodur et al. (2004a). It would appear that cracking in the tested HSC columns played a significant role in the fire endurance as spalling. In each column tested, diagonal corner cracks, as illustrated in Fig. 6, formed in the first 30 min of the test. The expansion of the unconfined cover concrete caused it to crack and sepa-

Fig. 6. Crack initiation in columns HS2-1 and HS2-3.

rate from the column at the corners, thereby exposing the confining ties to the fire. The 135° ties anchored back into the core of the column and maintained confinement of the column even in this exposed state.

All six columns failed in compression mode. In all columns, there was noticeable spalling at the end of the test and columns HS2-1 and HS2-6 failed in a ductile mode. Some degree of spalling occurred in all columns, however, the extent of spalling (severity) and the stage at which it occurred varied for each case. At higher load levels and under eccentric loads, a significant amount of spalling occurred just prior to failure of the columns. This is in contrast to the earlier studies on NSC columns, where only slight significant spalling occurred at failure of the columns (McGrath and Kodur 2000).

Spalling was generally very minimal in columns HS2-1 to HS2-3 and very significant in columns HS2-4 to HS2-6. In columns HS2-1 to HS2-3 spalling was minimal at early stages of fire exposure, nonexistent at intermediate stages, and moderate in the final stages of fire exposure (prior to failure). In columns HS2-4 to HS2-6, spalling was very minimal in initial stages of fire exposure, significant at intermediate stages, and very significant in the final stages of fire exposure. The observed spalling is summarized in Table 2. This variation in spalling in different columns can be attributed to the factors such as the presence of silica fume, aggregate type, and loading type.

Columns (HS2-1 to HS2-3) made with carbonate aggregate concrete and no silica fume exhibited very little spalling as compared with columns (HS2-4 to HS2-6). This could be attributed to the effect of aggregate as well as the absence of any silica fume in columns HS2-1 to HS2-3. Due to the endothermic reaction in carbonate aggregate, the specific heat of carbonate aggregate concrete, above 600°C temperature, is generally much higher than that of siliceous aggregate concrete. This heat is approximately 10 times the heat needed to produce the same temperature rise in siliceous aggregate concrete. This increase in specific heat is caused by the dissociation of the dolomite in the carbonate concrete

and is beneficial for fire endurance and also in reducing spalling of concrete (Kodur 2000; Lie 1993). In contrast, columns HS2-4 to HS2-6 had higher spalling during intermediate stages of fire exposure and prior to failure. This could be attributed to the presence of higher silica fume and siliceous aggregate in the concrete.

An approximate idea on the extent and nature of spalling as well as the failure pattern can be gauged from Figs. 7 and 8 that show typical view of columns HS2-1 and HS2-4 after fire endurance tests.

Fire endurance

A comparison of fire endurance for all columns is given in Table 1. The time to reach failure is defined as the fire endurance of the column. When steel reinforcement yields, concrete carries a progressively increasing portion of the load. The strength of concrete also decreases with temperature, and ultimately when the column can no longer support the load, failure occurs.

High strength concrete columns, HS2-1 to HS2-3, attained higher fire endurance as compared with other columns. The decreased fire endurance for HSC columns (HS2-4 to HS2-6) as compared with the columns HS2-1 to HS2-3 can be attributed to a number of factors including the mix proportions of the concrete. Further, significant spalling that results in the decrease in the cross section at later stages of fire exposure also contributed to lowering the fire endurance of HSC columns HS2-4, HS2-5, and HS2-6.

A comparison of fire endurance of various columns indicates that columns HS2-1 to HS2-3 had the highest fire endurance, while columns HS2-4 to HS2-6 had the lowest fire endurance in the series. Columns HS2-1 to HS2-3, made with carbonate aggregate and no silica fume, had higher fire resistance than columns HS2-4 to HS2-6, which were made with silica fume and siliceous aggregate. It has been shown in earlier studies that the presence of carbonate aggregate increases fire resistance of concrete columns by about 10%–15% (Kodur 2000; Lie and Celikkol 1991; Kodur et al. 2003). Thus, the substantial decrease in fire endurance of

Fig. 7. View of HSC column HS2-1 after fire endurance test.

HSC columns HS2-4 to HS2-6, as compared with HS2-1 to HS2-3, can be attributed to the effect of silica fume.

Effect of silica fume and lateral confinement on fire endurance

Data from the above experimental studies as well as the data from earlier studies (Kodur and McGrath 2003; McGrath and Kodur 2000; Kodur et al. 2003) indicate that good fire endurance can be obtained for HSC columns. However, HSC columns must be reinforced with increased levels of confinement reinforcement over that used in NSC columns if the same fire endurance ratings are to be achieved by both types of columns (Kodur and McGrath 2003; McGrath and Kodur 2000).

Based on the analysis of experimental data reported above and the visual observations made during and after the fire endurance tests, some of the factors that influence the fire performance of HSC columns are briefly discussed below. However, it should be noted that fire endurance depends on a number of factors and many of the factors are interdependent.

Effect of silica fume

A comparison of the various fire endurance in Table 1 indicates that silica fume and associated concrete strength

Fig. 8. View of HSC column HS2-4 after fire endurance test.

have an influence on fire endurance. The fire endurance of HSC columns HS2-4 to HS2-6 is much lower than columns HS2-1 to HS2-3. These two sets of columns had two variations in their characteristics: concrete strength and associated extent of silica fume and the type of aggregate. In this section, the effect of silica fume and associated concrete strength that contributed to lowering the fire endurance in columns is discussed. Also, a comparison of the fire endurance in Table 1 with that of normal strength concrete columns (NBCC 1995; Lie and Woollerton 1988) indicate that the HSC columns have the lower fire endurance of the two. While for NSC columns a fire endurance of about 6 h was obtained (Kodur and Sultan 1998), for HSC columns, with similar confinement, fire endurance of only about 4 h was obtained.

The fire endurance of columns HS2-1, HS2-2, and HS2-3 are 299, 343, and 379 min, respectively, while for columns HS2-4, HS2-5, and HS2-6 it was 146, 108, and 142 min, respectively. Columns HS2-1 to HS2-3 were fabricated from concrete mix without any silica fume and with a compressive strength of 81 Mpa, whereas columns HS2-4 to HS2-6

were fabricated from concrete mix with about 15% silica fume and had a compressive strength of 114 MPa. Also, the extent of spalling was very significant in columns HS2-4 to HS2-6, while it was only moderate in columns HS2-1 to HS2-3. The higher silica fume and associated compressive strength increases the extent of spalling because of increased compactivity and leads to decreased fire endurance. This could be attributed to the fact that the addition of silica fume appears to reduce the permeability of the concrete by restricting the loss of moisture during curing, drying, and the fire test. Further research is needed to quantify the exact extent of silica fume on spalling and fire endurance of HSC members.

Effect of lateral confinement

Test results from batch 1 (HS2-2 and HS2-3) and batch 2 (HS2-5 and HS2-6) columns can be used to study the influence of confinement on the fire performance of HSC columns. In all columns the ties were bent 135° back into the core of the column, since it has been clearly shown in earlier studies that higher fire endurance and minimal spalling can be obtained by better detailing of the column ties (ties were bent 135° back into the core of the column and increased lateral reinforcement) (Kodur and McGrath 2003; McGrath and Kodur 2000; Kodur et al. 2003). Some columns had increased lateral reinforcement.

The fire endurance of columns HS2-2 and HS2-3 is 343 and 379 min, respectively, whereas for columns HS2-5 and HS2-6 it was 108 and 142 min, respectively. In columns HS2-3 and HS2-6, the ties were spaced at a distance of h , while in columns HS2-2 and HS2-5 the spacing of ties was at $3/4h$. The higher fire endurance in columns HS2-3 and HS2-6 as compared with columns HS2-2 and HS2-5 can be attributed to better detailing of the column ties (to the presence of cross-ties).

No conclusive evidence can be drawn with respect to the effect of tie spacing from the limited data reported in this study. Variations in test loads and aggregate type do not permit a statistical analysis of the effect of tie spacing. What is apparent from these tests, however, when compared with similar specimens tested earlier with conventional 90° ties (Kodur and McGrath 2003) is that the use of ties with 135° hooks greatly enhances the fire resistance and the failure mode of the columns. It should be noted that columns HS2-3 and HS2-6, with the largest tie spacing of h , also employed cross-ties that served to increase the efficiency of the confinement at the level of ties. The columns employing ties at a spacing less than h did not use these cross-ties.

Summary

Based on above-mentioned experimental studies it was found that

- High fire endurance, up to 6 h, can be obtained for HSC columns under certain conditions. The silica fume and associated increased concrete strength, detailing of ties, and type of aggregate influence the fire performance of HSC columns.
- In all columns, no significant spalling was observed in the initial stages of fire exposure. Generally, the spalling in

HSC columns was significant only toward the end of the tests.

- The fire endurance of HSC columns with higher silica fume content is lower than that of HSC columns with lower levels of silica fume. Also, the higher the silica fume content, the higher the extent of spalling.
- The reduced tie spacing and the provision of cross-ties is beneficial in minimizing the spalling in HSC.
- The type of aggregate has a visible influence on the performance of HSC columns at elevated temperatures. The presence of carbonate aggregate in HSC increases fire endurance. Also, the extent of spalling is generally much lower for carbonate aggregate columns as compared with those of siliceous aggregate concrete columns.
- The authors recommend that numerical fire endurance modeling studies be conducted to define the relationship of the investigated variables to fire endurance. The experimental data presented in this paper can be used to validate the numerical fire endurance methodology.

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