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Construction Technology Update No. 31

Fire Performance of High-Strength Concrete Structural Members

by V.K.R. Kodur

The increased use of high-strength concrete in buildings and structures has led to concerns about its fire performance, especially the problem of spalling. This Update presents research results comparing the fire resistance of high-strength and normal-strength concrete columns and offers guidelines for improving the fire resistance of high-strength concrete structural members.

Figure 1. View of (a) normal-strength concrete column and (b) high-strength concrete column after fire-resistance tests

High-strength concrete (HSC) provides a high level of structural performance, especially in strength and durability, compared to traditional, normal-strength concrete (NSC). Previously employed in bridges, offshore structures and infrastructure projects, HSC has seen increased use in high-rise buildings, especially for columns. The higher compressive strength of HSC allows for the use of smaller-diameter columns, which increases the amount of usable space in a building.

In building design, the provision of appropriate fire resistance for structural members is a major requirement. The fire resistance of a structural member is dependent on its geometry, the materials used in its construction, the load intensity and the characteristics of the fire itself. The recent version of CSA Standard CSA-A23.3-M94 ("Design of Concrete Structures") provides detailed provisions for the design of HSC structural members. However, there are no specific guidelines for evaluating the fire performance of HSC in either this standard or the National Building Code of Canada 1995 (NBC).

The Spalling Problem

Generally, concrete structural members perform well under fire situations. Studies show, however, that the performance of HSC differs generally from that of NSC and may not exhibit good fire performance. Spalling under fire conditions is one of the major concerns with HSC, a problem that is due to its low water/cement ratio.[1] Spalling has been observed under both laboratory and actual fire conditions (see Figure 1). A fire in the English Channel tunnel in 1996, for example, caused severe damage to tunnel rings owing to the spalling of concrete and resulted in injuries to eight people and a property loss of £50 million.[2] The spalling was attributed to the high strength of the concrete.

Spalling results in the rapid loss of the surface layers of the concrete during a fire. It exposes the core concrete to fire temperatures, thereby increasing the rate of transmission of heat to the core concrete and the reinforcement. Since the spalling occurs in the initial stages of a fire, it may pose a risk to evacuating occupants and firefighters.

Spalling is attributed to the build-up of pore pressure during heating. HSC is believed to be more susceptible to this pressure build-up because of its low permeability, compared to that of NSC.[3,4] The extremely high water vapour pressure, generated during exposure to fire, cannot escape because of the high density (and low permeability) of HSC. This pressure often

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Institute for Research in Construction

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reaches the saturation vapour pressure, which at 300°C is about 8 MPa. Such internal pressures are often too high to be resisted by the HSC, which has a tensile strength of about 5 MPa.

Fire Performance of HSC and NSC

Research is in progress at NRC's Institute for Research in Construction (IRC) to evaluate the fire performance of HSC and to develop solutions that will minimize spalling and enhance fire resistance.

> At IRC, both experimental and numerical studies are being carried out to develop fire-resistance design guidelines for incorporation into codes and standards. In the experimental studies, 20 full-scale loaded HSC columns and a number of HSC blocks are being exposed to fire in a specially built furnace, in order to examine the influence of various parameters on the fire performance of HSC. The research is being conducted in partnership with the Portland Cement Association, the Canadian Portland Cement Association, Concrete Canada, CANMET, MOBIL and National Chiao Tung University, Taiwan.

Typical results from an IRC fire-resistance test involving NSC and HSC columns are shown in Figures 2 and 3 (aside from the concrete strength, the two types of columns were similar and were subjected to comparable loads).[3,4]

Figure 2 shows that temperatures, recorded at various depths from the surface, at mid-height of the column, are generally lower for the HSC column than for the NSC column throughout the fire exposure. These differences can be attributed partly to the differences in the thermal properties of the two concretes and to the higher compactness (lower porosity) of HSC. The lower porosity of HSC retards the rate of increase in temperature until the cracks widen and spalling occurs. Large cracks occurred in the HSC column after approximately three hours of fire exposure.

Figure 3 shows that the deformation of the HSC column is significantly lower than that of the NSC column. This can be explained in part by the lower thermal expansion of HSC and the slower rise in temperature in the HSC column during the initial stages of fire exposure due to the compactness of HSC.

As the temperature continues to rise, the steel reinforcement in both the NSC column and the HSC column gradually yields and the column contracts. When this happens, the concrete carries a progressively increasing portion of the load. The strength of the concrete also decreases with time and, ultimately, when the column can no longer support the load, failure occurs.

At this stage, the column behaviour is dependent on the strength of the concrete (Figure 3). There is significant contraction in the NSC column leading to gradual (ductile) failure. The lower contraction in the HSC column can be attributed to the fact that at elevated temperatures HSC becomes brittle and loses strength faster than NSC.

An important finding in the research was that while there was no spalling in the NSC column, there was significant spalling at the corners of the HSC column just before failure. There was also some spalling in the HSC column in the initial stages of fire exposure. Figure 1 shows the condition of the two types of columns after the fire resistance tests. In the HSC column, the reinforcement (both longitudinal and transverse) is completely exposed and there is significant spalling.

For the NSC columns, the fire resistance was approximately 366 minutes, while for HSC columns it was 225 minutes. The lower fire resistance for the HSC column can be explained by the thermal and mechanical properties of HSC. Furthermore, the spalling phenomenon, which resulted in a decrease in the cross-section of the column, also contributed to the lower fire resistance of the HSC columns.

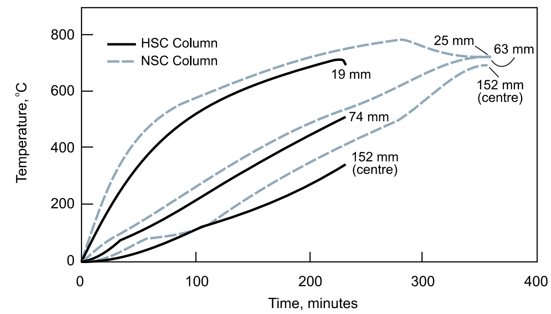

Figure 2. Temperature distribution at various depths during fire exposure in normal-strength concrete (NSC) and high-strength concrete (HSC) columns

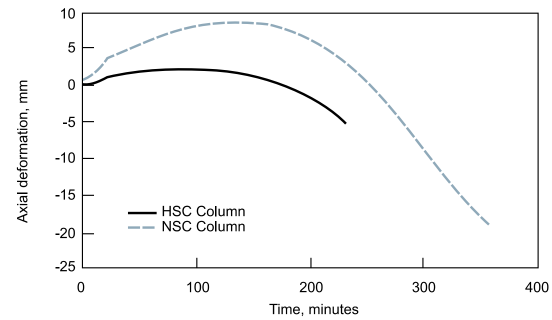

Figure 3. Axial deformation of normal-strength concrete (NSC) and high-strength concrete (HSC) columns during fire exposure

Factors Affecting Fire Performance

Research at IRC and elsewhere shows that the fire performance of HSC, in general, and spalling, in particular, is influenced by the following factors:

- original compressive strength of the concrete
- moisture content of the concrete
- density of the concrete
- fire intensity
- dimensions and shape of specimens
- lateral reinforcement
- loading conditions
- type of aggregate

The studies underway at IRC are seeking to quantify the influence of the above factors and to develop solutions to enhance the fire performance of HSC. So far it has been possible to draw some conclusions with regard to these factors, as discussed below.

Concrete Strength

While it is hard to specify the exact strength range, based on the available information, concrete strengths higher than 55 MPa are more susceptible to spalling and may result in lower fire resistance.

Moisture Content

The moisture content, expressed in terms of relative humidity, influences the extent of spalling. Higher RH levels lead to greater spalling. Fire-resistance tests on full-scale HSC columns have shown that significant spalling occurs when the RH is higher than 80%. The time required to attain an acceptable RH level (below 75%) in HSC structural members is longer than that required for NSC structural members because of the low permeability of HSC. In some cases, such as in offshore structures, RH levels can remain high throughout the life of the structure and should therefore be accounted for in the design.

Concrete Density

The effect of concrete density was studied by means of fire tests on normal-density (made with normal-weight aggregate) and lightweight (made with lightweight aggregate) HSC blocks.[5] The extent of spalling was found to be much greater when lightweight aggregate is used. This is mainly because the lightweight aggregate contains more free moisture, which creates higher vapour pressure under fire exposures.

Fire Intensity

The spalling of HSC is much more severe in fires characterized by fast heating rates or high fire intensities. Hydrocarbon fires pose a severe threat in this regard. When HSC is to be used in facilities where hydrocarbon fuels are present, such as offshore drilling structures and highway tunnels, the probable occurrence of spalling should be considered in the design.

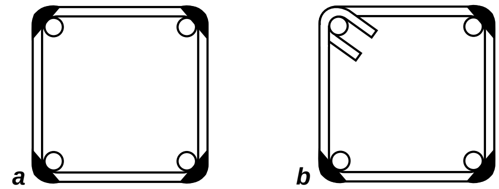

Figure 4. Tie configuration for reinforced concrete column: (a) conventional tie configuration; (b) modified tie configuration

Specimen Dimensions

A review of the literature shows that the risk of explosive thermal spalling increases with specimen size. This is due to the fact that specimen size is directly related to heat and moisture transport through the structure, as well as the capacity of larger structures to store more energy. Therefore, careful consideration must be given to the size of specimens when evaluating the spalling problem; fire tests are often conducted on small-scale specimens, which can give misleading results.

Lateral Reinforcement

The spacing and configuration of ties both have a significant effect on the performance of HSC columns. Both closer tie spacing (at 0.75 times that required for NSC columns) and the bending of ties at 135° back into the core of the column, as illustrated in Figure 4, enhance fire performance. The provision of cross ties also improves fire resistance. Fire tests on HSC columns, with additional confinement through cross ties and bending of ties back into the core of the column, have shown that spalling is significantly reduced and fire resistance as high as 266 minutes can be achieved even under full service loads.[3]

Load Intensity

A loaded HSC structural member will spall to a greater degree than an unloaded member. The load adds to the stresses created by the pore pressure generated by steam. Also, a higher load intensity leads to lower fire resistance, since the loss of strength with a rise in temperature is greater for HSC than for NSC.

Type of Aggregate

Of the two commonly used aggregates, carbonate aggregate (predominantly limestone) provides higher fire resistance and better spalling resistance in concrete than does

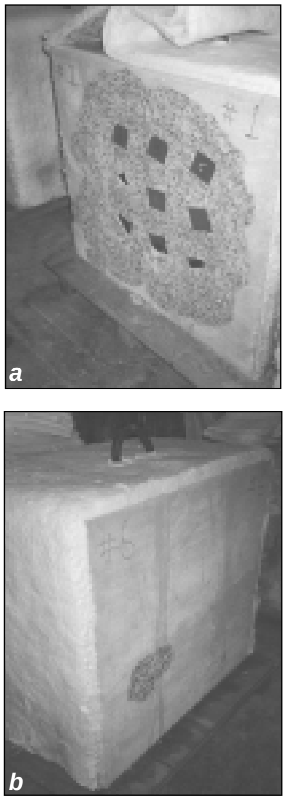

Figure 5. *View of high-strength concrete blocks after two-hour hydrocarbon fire test: (a) block without polypropylene fibres; (b) block with polypropylene fibres*

siliceous aggregate (predominantly quartz).[3] This is mainly because carbonate aggregate has a substantially higher heat capacity (specific heat), which is beneficial in preventing spalling. This increase in specific heat is likely caused by the dissociation of the dolomite in the carbonate concrete.

Fibre Reinforcement

The addition of polypropylene fibres minimizes spalling in HSC members under fire conditions.[1] One of the most accepted theories on this is that by melting at a relatively low temperature of 170°C, the polypropylene fibres create "channels" for the steam pressure in concrete to escape, thus preventing the small "explosions" that cause spalling. The study showed that the amount of polypropylene fibres needed to minimize spalling is about 0.1 to 0.25% (by volume). Further research is being carried out to determine the optimum fibre content for different types of concrete. The effect of polypropylene fibres on spalling is illustrated in Figure 5, which shows HSC concrete blocks after two hours of fire exposure.[5]

Steel fibres also reduce spalling in HSC and improve fire resistance. The fibres enhance the tensile strength of concrete, even at high temperatures, and help to withstand the pore pressure generated due to vapourization of water under fire exposure. With these fibres the tensile strength increases to between 5 and 7 MPa, which in many cases may be sufficient to achieve two to three hours of fire resistance without significant spalling. Full-scale tests have shown that the use of steel fibres in HSC significantly improves the fire-resistance performance of HSC-filled tubular steel columns.[6] However, when the pore pressure exceeds the tensile strength of concrete, spalling may still occur.

Guidelines for Enhancing Fire Performance

High-strength concrete is a high-performing material that offers a number of advantages. Engineers can enhance its fire performance by adopting the following guidelines:

- Use normal-weight aggregate (instead of lightweight aggregate) to minimize spalling.
- Add polypropylene fibres to the mix to reduce spalling.
- Add steel fibres to enhance tensile strength and reduce spalling.
- Use carbonate aggregate (instead of siliceous aggregate) to reduce spalling.
- Employ both closer tie spacing and cross ties to improve fire resistance.
- Install bent ties (at 135° back into the concrete core) instead of straight ties.
- Take appropriate precautions to prevent spalling when concrete strength exceeds 55 MPa.

Summary

The attractive properties of high-strength concrete must be weighed against concerns about its fire resistance and its susceptibility to spalling at elevated temperatures. Research at IRC is continuing and will result in more precise design guidelines.

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December 1999
ISSN 1206-1220

"Construction Technology Updates" is a series of technical articles containing practical information distilled from recent construction research.

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