Guidelines for Fire Resistance Design of High-strength Concrete Columns

V. K. R. KODUR*
Institute for Research in Construction
National Research Council, Canada

ABSTRACT: An overview of the research program, aimed at developing fire resistance design guidelines for high-strength concrete (HSC) columns, is outlined. A comparison is made of the fire resistance performance of an HSC column with that of a normal-strength concrete (NSC) column. The various factors that influence the structural behavior of HSC columns under fire conditions are discussed. Design guidelines are presented for mitigating spalling and enhancing fire endurance of HSC columns.

KEY WORDS: fire resistance, high-strength concrete, design guidelines, reinforced concrete columns, spalling.

INTRODUCTION

IN RECENT YEARS, the construction industry has shown significant interest in the use of high-strength concrete (HSC). This is due to the improvements in structural performance, such as high strength and durability, that it can provide compared to the traditional normal-strength concrete (NSC). HSC, which was widely used in applications such as bridges, off-shore structures, and infrastructure projects, has been extended to building columns. Often, HSC columns form the main load bearing component of a building envelope and hence, the provision of appropriate fire safety measures for these columns is one of the major safety requirements in building design. The basis for this requirement can be attributed to the fact that, when other measures for containing the fire fail, structural integrity is the last line of defense.

Generally, concrete structural members (mainly NSC) exhibit good performance under fire situations. However, results from a number of

*E-mail: Venkatesh.Kodur@nrc-cnrc.gc.ca

1042-3915/05/02 0093–14 $10.00/0 DOI: 10.1177/1042391505047740

studies [1–3] have shown that there are well-defined differences between the properties of HSC and NSC at high temperatures. Further, concern has developed regarding the occurrence of explosive spalling when HSC is subjected to rapid heating, as in the case of a fire [4–6].

Building codes, such as the National Building Code of Canada (NBCC) [7], generally specify fire resistance requirements for structural members. In North America, concrete structures are to be designed in accordance with the American Concrete Institute (ACI) standard [8] in the USA and the CSA A23.3-M94 standard [9] in Canada. The recent edition of the CSA standard contains detailed specifications on the design of HSC structural members; however, there are no guidelines for the fire resistance design of HSC structural members either in the CSA standard [9] or the ACI standards [8,10].

Studies are in progress at the National Research Council of Canada (NRCC), in partnership with the concrete industry and the international research organizations, to develop fire resistance design guidelines for the use of HSC in buildings and for the possible incorporation in codes and standards [11–13]. The main objective of this research is to understand the behavior of HSC columns and quantify the influence of various factors on the fire performance of HSC columns. As part of these studies, both experimental and numerical studies were carried out on full-scale reinforced concrete columns. Based on the results from these studies, preliminary guidelines have been developed for mitigating spalling and enhancing the fire endurance of HSC columns. These guidelines are presented in this paper.

RESEARCH SIGNIFICANCE

A review of the literature indicates that the fire performance of HSC is different from that of NSC and may not exhibit good performance in fire [1,2,6]. Furthermore, the spalling of concrete under fire conditions is one of the major concerns due to the low permeability of HSC. The spalling of concrete exposed to fire has been observed under laboratory and real fire conditions [2,6,11]. 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 and to the reinforcement.

Spalling is theorized to be caused by the build-up of pore pressure during heating [2,6,11]. HSC is believed to be more susceptible to this 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 often reaches the saturation vapor 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 [2]. Data from various studies show that predicting fire performance of HSC, in general, and spalling, in particular, is very complex since it is affected by a number of factors [1,6,11].

Many of the earlier studies have focused on understanding the mechanism of spalling and in quantifying the factors influencing spalling in HSC. Based on these studies, spalling can be minimized by incorporating measures such as adding polypropylene fibers or by providing external fire protection to concrete members [1,6,11,13].

The fire resistance of a structural member is dependent on the geometry, the materials used in construction, the load intensity, and the characteristics of the fire exposure itself. Fire endurance of an HSC member depends not only on the extent of spalling but also on the rate of loss of strength in the concrete. Further, achieving the required fire endurance in an HSC member through improved design, rather than through external fire protection, will enhance the cost-effectiveness and the aesthetics of the overall structural system.

The focus of most of the earlier studies was limited to exploring measures for mitigating spalling in HSC [2,4,6]. These measures were based on limited studies on small-scale specimens [2,5,14]. The focus of the current investigation is to evaluate the overall fire endurance of HSC columns, which depends not only on the extent of spalling but also on the overall behavior of an HSC member in fire. Data from the studies is used to develop design guidelines for mitigating spalling and enhancing the fire endurance of HSC columns.

FIRE RESISTANCE STUDIES ON HSC

Experimental Studies

The experimental program consisted of conducting fire resistance tests on a number of full-scale reinforced concrete columns. The test variables included column dimensions, concrete strength, type of aggregate in the concrete, tie configuration, addition of fiber reinforcement, type of fiber, load intensity and eccentricity of loading. Both NSC and HSC columns were considered in the study. All columns were of 3810 mm length and were designed according to CSA specifications [9]. The 28-day compressive strength of concrete was varied from about 34 MPa (typical for NSC) to about 110 MPa (typical for HSC), with most columns being in the range of 80–100 MPa. Type-K chromel–alumel thermocouples, 0.91 mm thick, were installed at midheight in the columns for measuring concrete temperatures at different locations in the cross section.

The tests were carried out by exposing the columns to heat in a furnace specially-built for testing loaded columns. The test furnace is designed to produce conditions such as temperature, structural loads, and heat transfer to which a member might be exposed during a fire. During the fire resistance test, the columns were exposed, under a load, to a heat controlled in such a way that the average temperature in the furnace follows, as closely as possible, the ASTM E119-2000 [15] standard temperature–time curve. The furnace, concrete and steel temperatures, as well as the axial deformations and rotations, were recorded until failure of the column.

During the 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 analyze the failure pattern, extent and nature of spalling, and condition of reinforcing bars and ties. The extent of spalling varied in different columns and was dependent on a number of factors.

Complete results from the experiments, including the furnace, concrete and steel temperatures, as well as the axial deformations of the column specimens recorded during the tests, are given in [3,12,13,16]. Also, details from observations, including the cracking pattern and spalling progression, are given in various papers [3,12,13,16] and some of these observations are used in quantifying the influence of various factors in the following sections. Typical results from two fire resistance tests are presented in the following section to illustrate the comparative performance of the NSC and HSC columns under fire conditions.

Behavior of HSC Columns

Typical results from fire-resistance tests involving the NSC and HSC columns are shown in Figures 1 and 2. Except for the concrete strength, the NSC and HSC columns had similar characteristics and were subjected to comparable load levels. The columns were of square cross section ($305 \times 305\,mm^2$) and 3810 mm long with the 28-day compressive strength of the NSC column being 34 MPa as opposed to 83 MPa for the HSC column. The variation of the cross-sectional temperatures for the NSC and the HSC columns is shown in Figure 1 as a function of the exposure time. These temperatures, measured during the fire tests, are shown for various depths from the surface along the centerline and at midheight of the column. It can be seen from Figure 1 that the temperatures in the HSC column are generally lower than the corresponding temperatures in the NSC column throughout the fire exposure. This variation can be attributed in part to the variation in the thermal and mechanical properties of the two concretes and to the higher compactness (lower porosity) of HSC. The low porosity

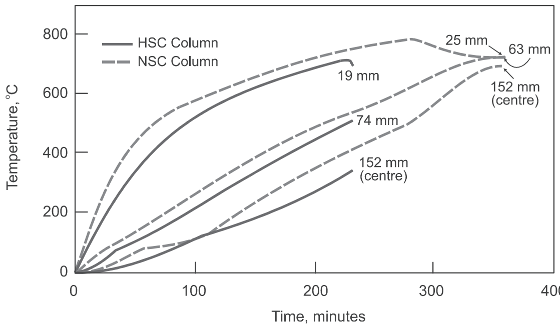


Figure 1. *Temperature distribution at various depths in the NSC and HSC columns.*

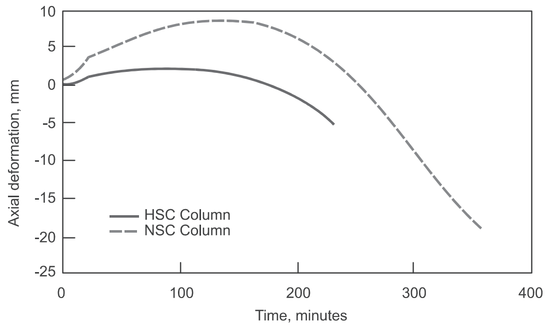


Figure 2. *Axial deformation for the HSC and NSC columns.*

of HSC affects the rate of increase of temperature in HSC until the cracks widen and spalling of the concrete occurs. Large cracks occurred in the HSC column only after approximately 3 h of fire exposure.

The variation of axial deformation with time is compared for the NSC and the HSC columns in Figure 2. It can be seen from the figure that the behavior of the HSC column is different from that of the NSC column. Both the NSC and the HSC columns expand until the reinforcement yields and then contract leading to failure. The initial deformation of the column is mainly due to the thermal expansion of both concrete and steel. In the case of the HSC column, the deformation is significantly lower than that of the NSC column. This can be attributed partly to the lower thermal expansion of HSC and the slower rise of temperature in the HSC column during the initial stages due to the high compactness of HSC. When the steel reinforcement in the column gradually yields, because of increasing temperatures, the column contracts.

When the steel yields, 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. In this stage, the behavior of the column is dependent on the strength of the concrete. There is a significant contraction in the NSC column leading to a gradual ductile failure. The contraction in the HSC column is much lower. This can be attributed to the fact that HSC becomes brittle at elevated temperatures and the strain attained at any stress level is lower than that attained in NSC for any given temperature. This is especially applicable for the descending portion of the stress–strain curve of HSC at elevated temperatures.

Based on the observations during and after the fire resistance tests, while there was no spalling in the NSC column, there was spalling at the corners toward the later stages of fire, prior to the failure occurred in the HSC column. Spalling, which results in the loss of concrete during a fire, exposes the deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the inner layers of the structure, including the reinforcement. The reinforcing bars in the HSC columns were fully exposed to fire during the later stages of fire. This spalling is due to the low permeability in HSC [1,11] and has also been observed in earlier studies on typical HSC structural members under laboratory and real fire conditions [1–3]. Figure 3 illustrates spalling in the NSC and the HSC columns after fire resistance tests and it can be seen that spalling in an HSC column is higher than that for an NSC column. However, it should be noted that the spalling was not significant in this HSC column, and this is mainly due to the provision of an improved tie configuration (further explained in a later section) that helps minimize spalling [16].

In these tests, the time to reach failure is defined as the fire resistance of the column. For the NSC column, the fire resistance is approximately 366 min while, for the HSC column, it is approximately 225 min. The decreased fire resistance for the HSC column, as compared to the NSC column, can be attributed to the faster degradation of the thermal and mechanical properties of HSC.

Numerical Studies

The main objectives of the experimental studies were to generate fire resistance data for immediate use by the construction industry, and to provide information for the development of general methods for calculating the fire resistance of the HSC columns. Mathematical models were developed for predicting the fire behavior of the HSC columns [17,18]. The steps, associated with the development of the models, involved the calculation of the fire temperatures, and the temperatures, deformations, and strength of the concrete–steel composite assembly. A simplified approach was used to account for spalling under fire conditions.

The models can take into account the influence of the various parameters that determine the fire performance of the HSC columns and can trace the response of an HSC column from the initial preloading stage to collapse, due to fire. The validity of the model has been established by comparing the results from the models to the test data [17,18]. The model is being used to carry out parametric studies to generate data on the fire resistance of HSC columns. The results of the preliminary parametric studies indicate that the fire resistance and the extent of spalling in the HSC columns are functions of a number of parameters including its size, the concrete strength, the load intensity, the tie configuration, the type of aggregate, and the type of fire intensity.

FACTORS GOVERNING FIRE PERFORMANCE

Data from the studies carried out at NRCC, as well as by a number of organizations world-wide [1,2,6], show that fire performance of HSC, in general, and spalling in particular, is complex and is affected by a number of factors. Based on the analysis of model predictions, test data, and the visual observations made during and after the fire tests, some of the factors that influence the fire endurance of the HSC columns are briefly discussed here.

Concrete Strength

The results from a number of fire resistance tests show that high fire endurance (three hours or more) can be obtained for the HSC columns even under full service loads. However, a comparison of the fire endurance of the HSC columns with that of the NSC columns [12,13] indicate that the HSC columns have the lower fire endurance of the two. However, the HSC columns must be reinforced with increased levels of confinement reinforcement (as prescribed in CSA-A23.3 [9]), over that used in the NSC columns, if the same fire endurance ratings are to be achieved by both types of columns. The spalling performance of an NSC column is compared to an HSC column in Figure 3 as observed from the full-scale fire tests on loaded columns [13]. It can be seen that the spalling is quite significant in the HSC columns.

While it is hard to specify the exact strength range, based on the available information, concrete strengths higher than 70 MPa are more susceptible to spalling and may result in lower fire resistance.

(a) NSC Column (b) HSC Column

Figure 3. Comparison of spalling in the NSC and HSC columns after fire resistance tests [3].

Concrete Moisture Content

The moisture content, expressed in terms of relative humidity (RH), influences the extent of spalling. Higher RH levels lead to greater spalling. The 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 the 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, the 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 the normal density (made with normal weight aggregate) and lightweight (made with lightweight aggregate) HSC blocks [19]. The extent of spalling was found to be much greater when the 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 [4,5]. 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 in the presence of fire should be considered in the design.

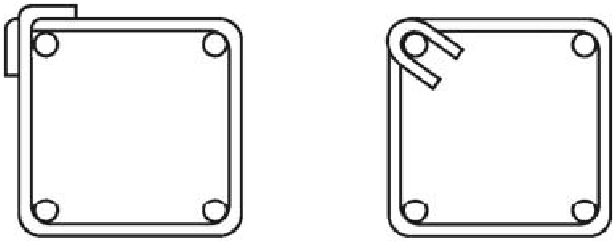
Specimen Dimensions

A review of the literature shows that the risk of explosive thermal spalling increases with the specimen size. This is due to the fact that the specimen size is directly related to the 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. However, when spalling mitigation measures (such as the one given in the following section) are incorporated, the risk of explosive spalling decreases and the fire resistance increases with the size of the members. Besides, similar cover thickness to reinforcement, as in the case for the NSC columns, based on structural (corrosion) considerations should be provided for the HSC columns.

Lateral Reinforcement

The results from the fire resistance studies clearly show that the layout of ties and confinement of columns have an influence on the fire performance of the HSC columns. Higher fire endurance in the HSC columns can be achieved by providing an improved tie configuration (provision of bent ties at 135° back into the core of the column and increased lateral reinforcement) and with a closer tie spacing (at 0.75 times that required for the NSC columns). Figure 4 shows a conventional and modified tie configuration for an HSC column. The provision of cross ties also improves fire endurance [10,14]. These provisions also minimize the extent of spalling in the HSC columns.

Figure 5 shows photographs of the column specimens, with the conventional and improved tie configuration, after the fire resistance tests. The extent of spalling in columns, with bent tie configuration, was relatively less compared to that in columns without bent tie configuration. The columns containing only 90° ties would typically lose a significant portion of the columns section upon failure. The columns using 135° ties



(a) Conventional tie configuration **(b) Modified tie configuration**

Figure 4. *The conventional and modified tie configurations for reinforced concrete columns.*

(a) Conventional tie configuration (b) Modified tie configuration

Figure 5. *Comparison of spalling in HSC columns after fire resistance tests [12].*

would exhibit the classic pyramid compression failure section with the failed section being confined locally to one or two tie spacing.

Fiber Reinforcement

Studies show that the addition of polypropylene fibers minimizes spalling in the HSC members under fire conditions [5,6,11]. One of the most accepted theories on this is that by melting at a relatively low temperature of 170°C, the polypropylene fibers create 'channels' for the steam pressure within the concrete to escape, thus preventing the small 'explosions' that cause spalling. The amount of polypropylene fibers needed to minimize spalling is about 0.1–0.15% (by volume) [5,13,19]. The addition of steel fibers enhances the tensile strength and reduces spalling [13,19].

Load Intensity and Type

The type of load and its intensity have a significant influence on spalling and the resulting fire resistance. The fire endurance of a column increases with a decreasing load. 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. A loaded HSC structural member is susceptible to higher spalling than an unloaded one. This is specially true in columns with a conventional tie configuration and subjected to loads greater than the service loads. This occurs because a loaded structural member is subjected to stresses due to load in addition to the pore pressure generated by steam. Further, the extent of spalling is higher if the load is of an eccentric (or bending) type since this will induce additional tensile stresses.

Type of Aggregate

Of the two commonly used aggregates, the carbonate aggregate (predominantly limestone) provides higher fire resistance and better spalling resistance in concrete than does the siliceous aggregate (predominantly quartz). This is mainly because the 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. In general, the fire endurance of the HSC columns made with carbonate aggregate concrete is 10% higher than the HSC columns made with siliceous aggregate concrete [11–13].

GUIDELINES FOR ENHANCING FIRE PERFORMANCE

High-strength concrete is a high-performing material that offers a number of advantages. In recent years, significant research has been undertaken to study the fire behavior of the HSC columns and to quantify the factors influencing their spalling and fire endurance. However, even-to-date, there are no specific guidelines in codes and standards for the fire resistance design of the HSC structural members.

By adopting appropriate measures, spalling in HSC can be minimized and the fire endurance can be enhanced even for concrete strength as high as

110 MPa. Based on these detailed studies at the NRCC and elsewhere [4–6], the following are some of the preliminary guidelines that can be implemented for enhancing fire performance:

- The size of the structural members has an influence on fire endurance and the provisions in the current standards specify minimum cross-sectional dimensions for the NSC columns. The recommended minimum dimensions for achieving the fire endurance ratings in the HSC columns (both square and circular) are:

1 h	300 mm
1–1/2 h	350 mm
2 h	400 mm
3 h or more	500 mm

These dimensions are relatively higher than those required for the NSC columns.

- Fire endurance and the extent of spalling is influenced by the tie configuration adopted for the column. Installation of bent ties (when the ties are bent at 135° into the concrete core) helps to minimize spalling and increases fire endurance (Figure 4). Provision of cross ties also improves fire resistance.
- Addition of polypropylene fibers, about 0.1–0.15% by volume, to the mix reduces spalling.
- Addition of steel fibers enhances tensile strength and reduce spalling [13,19].
- Use of carbonate aggregate, instead of siliceous aggregate, reduces spalling and enhances fire endurance.
- The spalling of HSC is much more severe in fires characterized by fast heating rates or high fire intensities such as hydrocarbon fire scenarios. 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. Addition of polypropylene fibers, about 0.1–0.15% by volume, to the concrete mix significantly reduces spalling.
- Provision of sufficient concrete cover thickness to reinforcement as specified in standards based on structural (corrosion) considerations.

SUMMARY

High-strength concrete is a high-performing material and offers a number of benefits over normal-strength concrete. However, there is a concern on the occurrence of spalling and lower fire endurance of HSC (as compared to

NSC). The type of aggregate, concrete strength, concrete density, load intensity, fire intensity, and tie configuration have an influence on the fire performance (both spalling and fire endurance) of the HSC columns. By adopting design guidelines, such as the addition of fibers and an improved tie configuration, spalling in the HSC members can be minimized to a significant extent and fire endurance can be enhanced. The polypropylene fibers are much more effective in minimizing spalling in HSC subject to hydrocarbon fires.

REFERENCES

1. Phan, L.T., "Fire Performance of High-Strength Concrete: A Report of the State-of-the-Art," National Institute of Standards and Technology, Gaithersburg, MD, 1996, p. 105.
2. Diederichs, U., Jumppanen, U.M. and Schneider, U., "High Temperature Properties and Spalling Behaviour of HSC," Proceedings of 4th Weimar Workshop on HPC, HAB Weimar, Germany, 1995, pp. 219–235.
3. Kodur, V.R. and Sultan, M.A., "Structural Behaviour of High Strength Concrete Columns Exposed to Fire," Proceedings: International Symposium on High Performance and Reactive Powder Concrete, Sherbrooke, Quebec, 1998, Vol. 4, pp. 217–232.
4. Danielsen, Ulf., "Marine Concrete Structures Exposed to Hydrocarbon Fires," Report, SINTEF – The Norwegian Fire Research Institute, 1997, pp. 56–76.
5. Bilodeau, A., Malhotra, V.M. and Hoff, G.C., "Hydrocarbon Fire Resistance of High Strength Normal Weight and Light Weight Concrete Incorporating Polypropylene Fibres," International Symposium on High Performance and Reactive Powder Concrete, Sherbrooke, QC, 1998, pp. 271–296,
6. Hertz, K.D., "Limits of Spalling of Fire-Exposed Concrete," Fire Safety Journal, 2003, Vol. 38, pp. 103–116.
7. National Research Council of Canada, National Building Code of Canada, Ottawa, ON, 1995.
8. ACI Committee 318, Building Code Requirements for Reinforced Concrete (ACI 318-95), American Concrete Institute, Detroit, 1995.
9. Canadian Standards Association, Code for the Design of Concrete Structures for Buildings. CAN3-A23.3-M94, Rexdale, ON, 1994.
10. ACI Committee 216, Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies, American Concrete Institute, Detroit, 1997.
11. Kodur, V.K.R., "Spalling in HSC Exposed to Fire: Concerns, Causes, Critical parameters and Cures," Proceedings, ASCE Structures Congress, Philadelphia, PA, 2000.
12. Kodur, V.K.R. and McGrath, R., "Performance of High Strength Concrete Columns Under Severe Fire Conditions," Proceedings Third International Conference on Concrete Under Severe Conditions, Vancouver, BC, Canada, 2001, pp. 254–268.
13. Kodur, V.K.R., Cheng, F.P. and Wang, T.C., "Effect of Strength and Fiber Reinforcement on the Fire Resistance of High Strength Concrete Columns," ASCE Journal of Structural Engineering, 2003, Vol. 129, No. 2, pp. 253–259.
14. Ali, F.A., Nadjai, A., Glackin, P. and Silcock, G., "Structural Performance of High Strength Concrete Columns in Fire," Proceedings of the Seventh International Association of Fire Safety Science Symposium, Worcester, MA, USA, 2002, pp. 1001–1012.
15. American Society for Testing and Materials, Standard Methods of Fire Endurance Tests of Building Construction and Materials, ASTM E119-00, Philadelphia, PA, 2000.

16. Kodur, V.R. and McGrath, R.C., ‘‘Fire Endurance of High Strength Concrete Columns,’’ Fire Technology – Special Issue, 2003, Vol. 39, No. 1.
17. Kodur, V.R., Wang, T.C., Cheng, F.P. and Sultan, M.A., ‘‘A Model for Evaluating the Fire Resistance of High Performance Concrete Columns,’’ Proceedings of the Seventh International Association of Fire Safety Science Symposium, Worcester, MA, USA, 2002, pp. 1013–10124.
18. Kodur, V.R., Wang, T.C. and Cheng, F.P., ‘‘Predicting the Fire Resistance Behaviour of High Strength Concrete Columns,’’ Cement and Concrete Composites Journal, 2004, Vol. 26, pp. 141–153.
19. Kodur, V.R., ‘‘Fibre-Reinforced Concrete for Enhancing the Structural Fire Resistance of Columns,’’ Fibre-Structural Applications of Fibre-Reinforced Concrete, ACI SP-182, 1999, pp. 215–234.