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Performance of High-Strength Concrete in Fire

By Venkatesh Kodur

This article presents some key results of studies carried out by NRC's Institute for Research in Construction, comparing the performance of normal-strength and high strength concrete columns in fire situations. Particular attention is devoted to the problem of spalling encountered with high-strength concrete.

As the use of high-strength concrete in buildings and other structures has increased, so too have concerns about its fire performance — especially the problem of spalling. As a result, the National Research Council's Institute for Research in Construction (IRC) is carrying out experimental and numerical studies to address these concerns. High-strength concrete (HSC) finds applications in the construction of bridges, offshore structures and infrastructure projects because of its improved structural performance, particularly in strength and durability, compared with normal-strength concrete (NSC). Its use has been extended to buildings in recent years, especially for columns. Its higher compressive strength allows for smaller columns, thus reducing costs. Smaller columns take up less space, which can have huge financial implications for structures like parking garages as more cars can be accommodated on each floor, thus increasing profits. Design professionals are always concerned about providing appropriate fire resistance for structural members. The most recent CSA standard for the design of concrete structures for buildings — CSA-A23.3-M94 — provides detailed guidelines for the design of HSC structural members. However, neither the standard nor the 1995 edition of the National Building Code of Canada provides specific guidelines for evaluating the fire performance of HSC.

Questioning HSC's fire performance

While concrete structural members generally perform well in fires, studies show the performance of HSC differs from that of NSC and in fact, may not perform as well. A major concern is spalling — a problem that has been seen in both laboratory tests and actual fires in the field. Figure 1 shows the extent of spalling in a NSC column (left) and a HSC column (right) after fire-resistance tests. (Note: the severity of the spalling on the column on the right.)

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 some of the spalling occurs in the initial stages of a fire, it may pose a risk to occupants evacuating the building and to firefighters.

Spalling may be attributed to the build-up of pore pressure during heating. HSC is thought to be more susceptible to this pressure build-up because of its low permeability compared with NSC. During a fire, the water within the concrete vapourizes, but the vapour cannot escape because the material is extremely dense with low permeability. As a result, internal pressure builds up as the heat increases and parts of the column surface spall.

Finding ways to minimize spalling

The goal of IRC's research is to develop solutions that will minimize spalling and enhance the fire resistance of HSC. When the work is complete, the results will be incorporated into codes and standards.

IRC's work on HSC is being conducted in partnership with the Portland Cement Association, the Canadian Portland Cement Association, Concrete Canada, CANMET, MOBIL and National Chiao Tung University in Taiwan. The experimental studies consist of exposing 30 full-scale loaded HSC columns to fire in a column furnace specially designed to conduct loaded column tests. The column furnace is one of a few such facilities in the world.

As a result of IRC's research and work done elsewhere, a number of factors have been identified as influencing the fire performance of HSC generally, and particularly the problem of spalling.

Fire performance of HSC

While more research remains to be done before definitive results are available for designers, it is possible to draw some conclusions from the research done thus far.

For example, it has been found that when the concrete strength is higher than 55 MPa, columns are more susceptible to spalling and may have lower fire resistance.

The density of aggregate used in the concrete mix was also found to have an effect. Tests on HSC blocks show spalling is much greater when lightweight aggregate is used versus normal-weight aggregate.

And, of the two types of aggregate commonly used in concrete, carbonate aggregate provides higher fire resistance and better spalling resistance than does siliceous aggregate. This is because carbonate aggregate has a substantially higher heat capacity.

IRC research included an investigation of the effect that might be achieved by the addition of fibres to HSC. (The addition of fibres also improves the general durability characteristics of concrete.) Polypropylene fibres were found to minimize spalling in a fire. The fibres melt at relatively low temperatures, creating "channels" by which the steam in the concrete can escape without causing the small "explosions" at the concrete's surface. Studies are continuing to determine the optimum fibre content for different types of concrete.

As well, studies have shown that closer tie spacing (at 0.75 times that required for NSC columns) and the bending of ties at 135 degrees back into the core of the column, as

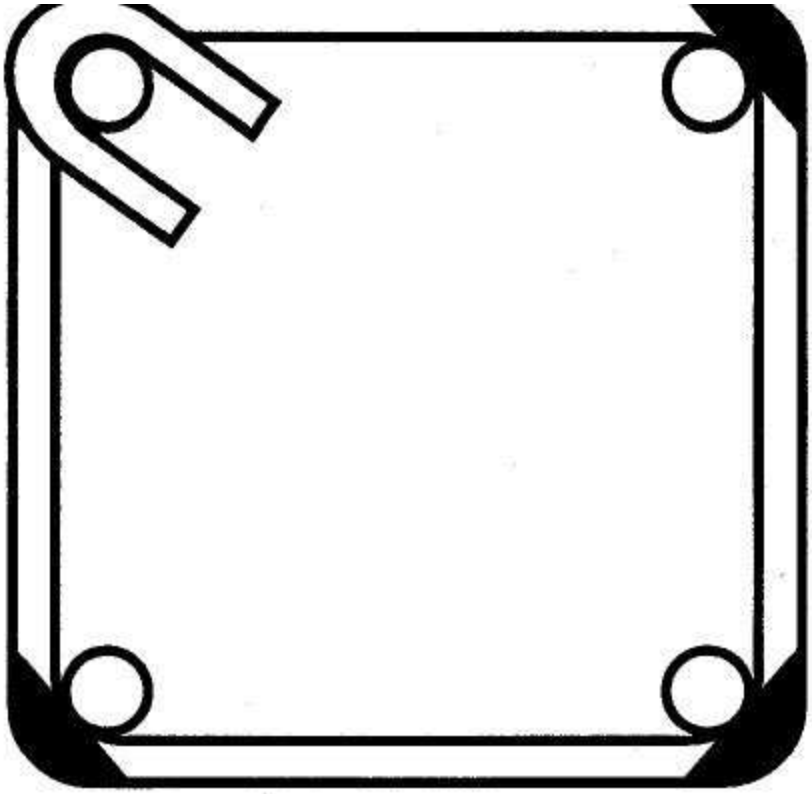
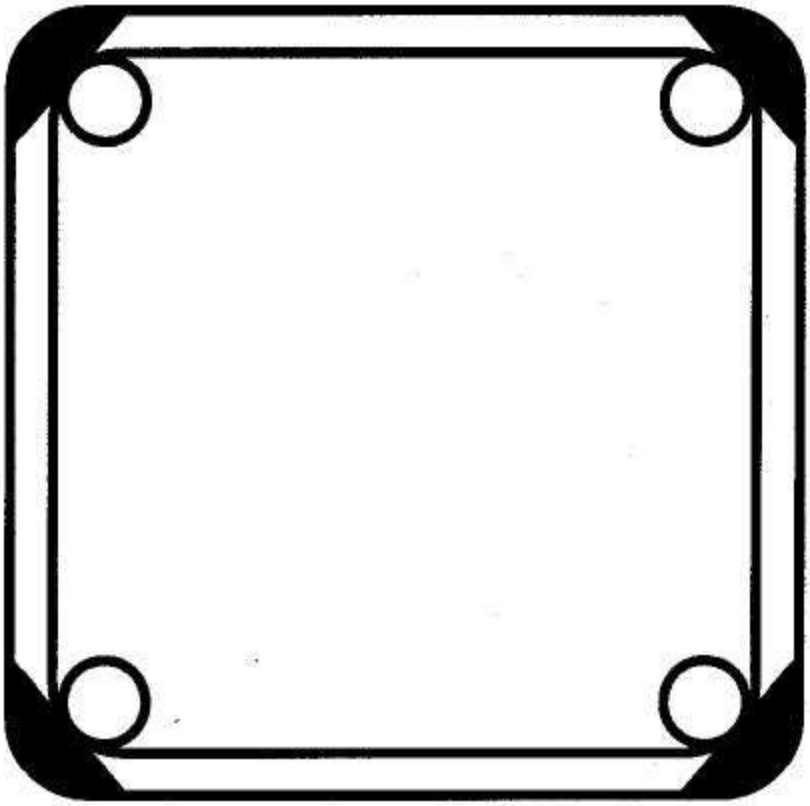


Figure 2



illustrated in Figure 2, enhances 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 at 135 degrees back into the core of the column, has shown a significant reduction in spalling with a fire resistance as high as 266 minutes, even under full service loads. Higher moisture content in the concrete, higher fire intensities and faster heating rates (as found in fires fuelled by hydrocarbons) leads to extensive spalling in HSC. However, fire intensity and heating rates are generally lower in building fires.

The results of the research done so far can be found in IRC's Construction Technology Updates series. The four-to-six-page Updates, 12 of which are published annually, summarize the latest advances in construction science and technology on specific topics.

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