Shotcrete in Fires: Effects of Fibers on Explosive Spalling

by Peter C. Tatnall

For those of us in the concrete industry, the events over the last year have caused many of us to focus on the effects of blasts and fire on concrete structures. Information on the effects of fire on normal strength concrete (NSC) less than 7000 psi (50 MPa) has been available since the 1950s.[1] On the other hand, little information on the behavior of high-strength or high-performance concrete (HPC) in fires has been developed until recent times, particularly with reference to thermal shock (high temperature rise rates) and sustained high temperatures.[2]

As a rule, HPC is more sensitive to high temperatures and thermal shock than NSC because of its reduced porosity, with smaller and fewer interconnected pores, leading to vapor pressure buildup. As the pore pressures increase, tensile stresses build in the concrete, and when they exceed the tensile strength of the concrete, explosive spalling occurs. Pieces of the hot-side concrete are violently dislodged from the structure exposing more concrete to the fire, eventually exposing the reinforcing systems to the fire's full effects. Rapid thermal expansion of some normalweight aggregates and, to a lesser extent, lightweight aggregates can contribute to explosive spalling as well.

Certainly shotcrete can be classified as high-performance concrete. Because of the compactive effort resulting from the shotcrete placement method, pore structures can be similar to cast HPC, and thus shotcretes are also at risk from the effects of fire. Until recently, very little research has been conducted on the effects of fire on shotcrete; however, catastrophic fires in tunnels, such as the Channel Tunnel and the Mont Blanc and St. Gotthard Tunnels in Europe, have sparked new interest in research on shotcrete and the effects of high temperature rise rate effects. Figure 1[3] shows the explosive spalling of the concrete lining of the Channel Tunnel after a rail-car fire in 1996. Eleven lives were lost, and over 600 ft (183 m) of the roof of the 10-mile (16 km) long St. Gotthard Tunnel collapsed after two trucks collided, causing a fire that burned for over 2 days at temperatures estimated at 2200 °F (1200 °C).

In fire testing, new time-temperature curves have been developed, as a result of these and more than 23 other tunnel fires, to simulate the effects of fires fed by hydrocarbon fuels, such as gasoline, diesel fuel, animal fats, and tires.[4] Furnace temperature rise rates are specified to increase at a rate of 400 °F (200 °C) per minute to 2000 °F (1100 °C) in 5 min, with final temperatures of 2460 °F (1350 °C), then held for two hours. This time-temperature curve (Rijkswaterstaat [RWS Curve]) is shown in Fig. 2.

Generally, damage to concrete or shotcrete due to fire is manifested by two distinct actions. In the first case, the moisture in the pores is driven away from the hot face of the shotcrete and the shotcrete paste dehydrates. As this occurs, the bond between the paste and aggregate is lost because of different thermal characteristics, and the shotcrete loses all structural capability and thin sections slowly slough off. This type of deterioration normally occurs for fires with a low rate of temperature rise, such as is specified in the ASTM E 119 Test Method.[5] As the moisture in the

Figure 1: Fire spalling of concrete lining in the Channel Tunnel 1996.[3]

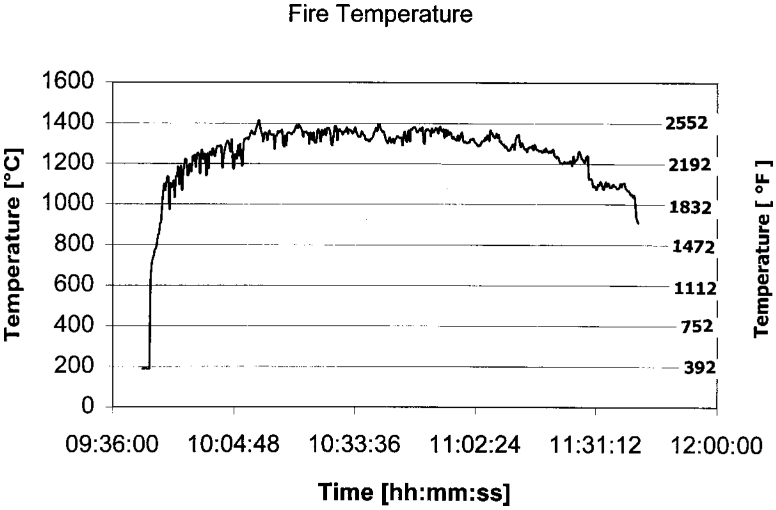

Figure 2: Furnace temperature versus time curve (RWS Curve).

shotcrete pores is converted to vapor (steam), there is time for it to migrate away from the hot face; and, in fact, the energy consumed in converting the moisture to vapor helps to reduce explosive spalling in these fires.

In the second case, the rate of temperature rise is so rapid that the moisture does not have time to move away from the hot side and pressure builds until it exceeds the tensile strength of the shotcrete. As a consequence, layers of shotcrete are violently dislodged, a new face is exposed to the fire, and the explosive spalling damage progresses deeper into the shotcrete structure. The research described as follows illustrates this phenomenon.

In 2001, S I Concrete Systems contracted with Hagerbach Test Gallery in Switzerland to investigate the effects of the RWS-Curve fires on fiber-reinforced shotcrete because of the concern expressed by designers and tunnel owners in Europe.[6] Square panels, 4 ft x 9 in. (1.45 m) x 6 in. (15 cm) thick were shot and cured for 28 days before testing. The basic shotcrete mixture used in all panels is shown in Table 1. One panel was shot without fibers but with a steel mesh reinforcing, typically used in shotcrete tunnel linings in Europe, placed at the center of the panel section. Another panel was shot with 66 lb/yd^3 (40 kg/m^3) steel fibers added as might be used for tunnel lining shotcrete. A third panel was shot with the 66 lb/yd^3 (40 kg/m^3) steel fibers plus 3 lb/yd^3 (1.8 kg/m^3) fine monofilament polypropylene (PP) fibers added. A fourth panel was shot with 15 lb/yd^3 (9 kg/m^3) of a coarse high performance polymer fiber similar in size and shape to the steel fibers used in the second panel.

All the panels were subjected to the RWS-Curve fire (Fig. 2) in a special-built furnace as shown in Fig. 3. A diesel fuel fire as shown was designed to spread flame on the test panels placed horizontally on the top of the furnace. Thermocouples were placed near the panel in the furnace and in the shotcrete panels at depths of 1-3/8 in. (30 mm) and 2-3/4 in. (70 mm) from the hot face of the panels. Connected to a computer, temperatures were monitored in real time.

The steel mesh-reinforced panel was tested first. After only a few minutes of fire exposure, investigators could hear loud popping sounds and pieces of shotcrete were seen bouncing off the floor of the furnace. After 15 min, they shut down the fire because of concerns that the explosive spalling would damage the fire testing equipment. The mesh-reinforced panel after testing in the furnace is shown in Fig. 3. Approximately 1/2 the thickness, 3 in. (7.5 cm), was lost due to explosive spalling in 15 min as shown in Fig. 4.

The third panel with steel fibers and 3 lb/yd^3 (1.8 kg/m^3) of micro PP fibers was tested for the full 2 h. The temperature-time curve for the thermocouples in the shotcrete are shown Fig. 5, and the hot face of this panel is shown in Fig. 6 after 2 h of fire testing. A small section on the upper face has dehydrated and sloughed off;[7] but, otherwise, the panel has suffered no explosive spalling-induced damage.

The second and fourth panels containing either steel or PP macro fibers, but no micro PP fibers, were tested and showed extensive explosive spalling. In fact, the macro PP fiber panel broke into five pieces.

Table 1: Shotcrete Mixture, lb/yd^3.

Cement	758
Water	347
Aggregate	4040
Steel fiber	66
w/c	0.46
Compressive strength	6525 psi

Figure 3: Hagerbach hydrocarbon-fueled fire furnace setup.

Figure 4: Nonfibrous mesh reinforced panel: 15-min fire test.

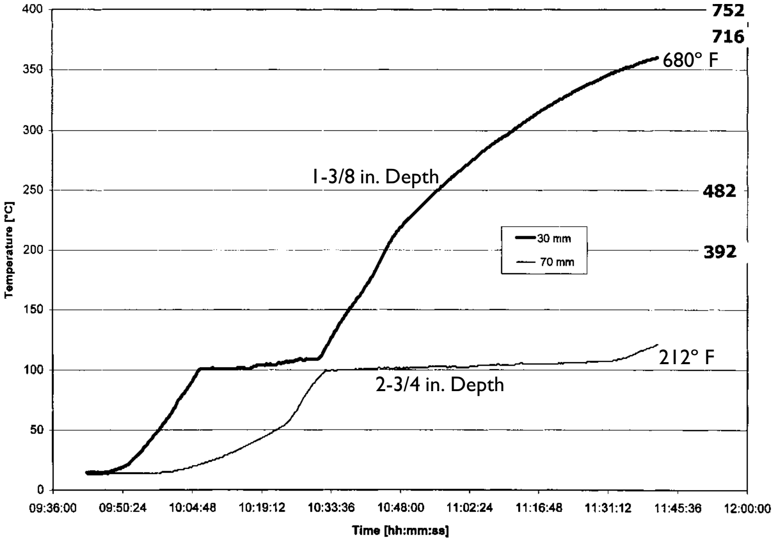

Figure 5: Thermocouple data for steel + PP fiber-reinforced shotcrete panel.

Figure 6: Steel + micro PP fiber shotcrete panel after 2-h fire test.

It has been demonstrated that the use of fine, micro polypropylene monofilament fibers (approximately 6 denier, or 0.0012 in. (30 µm) diameter) mitigates the effects of explosive spalling of concrete in hydrocarbon-fuelled fires.[8,9] The quite different thermal characteristics of the polypropylene fibers and the shotcrete matrix cause small fissures to open at the fiber-matrix interface as the fibers expand at a different rate than the matrix when heated.[8] These small openings allow the escape of the building vapor pressure. The results of the Hagerbach shotcrete investigation showed that shotcrete can be made fire resistant using the same technology. Furthermore, the Hagerbach testing shows that macro fibers of steel or polypropylene do not effect the explosive spalling behavior of shotcrete in RWS-Curve fires. This is most likely due to the difference in the number of fibers in the matrix—more than 52 million fibers per pound (114 million fibers per kg) for the micro PP fibers used versus only 9000 to 13,000 fibers per pound (20,000 to 30,000 fibers per kg) for the macro fibers used.

This testing and other investigations have resulted in the use of both steel and micro monofilament polypropylene fibers in the precast segments and shotcrete linings for the 25 miles (40 km) of the Channel Tunnel Rail Link tunnels being presently constructed in the UK.[10] The susceptibility of high-performance concrete to explosive spalling in fires can be mitigated with the proper use of micro PP fibers. This very inexpensive insurance can protect the lives of those trying to escape the fire as well as those fighting the fire. Preventing catastrophic collapse of structures can help to significantly reduce repair costs, save lives, and reduce the severe disruption to commerce using these facilities.

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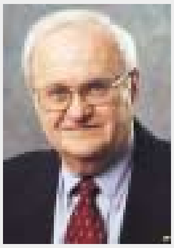

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