Nylon Fibres Eliminate and Silica Fume Does Not Increase the Risk of Explosive Spalling of HPC In Fire

Report By : Frank Papworth

Cause Of Concern

When concrete is subject to a fire some water in the concrete escapes from the surface while other water is pushed back into the concrete. As the fire continues and the heat builds up water is pushed further back into the concrete. As the fire continues more and more water is endeavouring to move away from the surface and, being restricted by the concretes impermeability pressure builds up. In some cases the pressure is so intense that the concrete spalls.

Silica fume concrete's low permeability has caused some to suspect that it will be more prone to explosive spalling in a fire. Results in some published papers support this while others do not. When the range of variables that effect explosive spalling (table 1) are considered it's likely that in some circumstances silica fume decreases the risk and in others it increases it.

Table 1: Silica Fumes Influence on Explosive Spalling.

Reducing The Risk

1. Higher tensile capacity ie will withstand the pressure
2. Self desiccation more likely reducing the water available

Increasing The Risk

1. Lower permeability ie more difficult for water to escape
2. Longer drying time gives more retained water at early age

On November 18th, 1996 34 people were trapped in dense smoke and darkness in a railway carriage while a fire raged around them for thirty minutes. The carriage was 150 feet below the Channel and 12 miles from shore. The fire raged for six hours. It took nearly 450 French and British firemen, working in relays, to eventually kill the flames. They later described it as "like a blow torch"; in fact, part of the train was welded to the track ***and the fabric of the tunnel itself was severely damaged***.

In 1998 Engineers for the new Singapore MRT considered it likely that the impermeability of the silica fume concrete was a major factor in the damage and limited the dosage of silica fume to 5% in their new tunnel.

Fig 1 – Life For 5% Silica Fume

Exposure	Tunnel - Reabsorption	
temperature (T) =	20	*°C*
hence surface chloride level (C_o) =	*3*	*wt%cement*
hence wet time for a spalsh (W_t) =	*0*	*min*
hence potential difference (v) =	*200*	*mv*
Concrete Quality		
w/c ratio (w)	0.35	
Silica fume content (f)	5	% by wt of cement
hence sorptivity (S) =	*0.08*	*mm/min$^{0.5}$*
hence diffusion coefficient (D_c)=	*8.3E-09*	*cm/sec^2* at 20C
hence diffusion coefficient (D_c)=	*8.3E-09*	*cm/sec^2* at given temp
hence resistivity (R)=	*18378*	*ohm cm*
Assume the concrete voids ratio (v)=	*0.1*	
Calculate Time To Activation (T_0)		
Cement Content (C_e)	400	kg/m^3
Cover (c)	40	mm
Assume critical chloride level (C_c) =	*0.4*	*wt % cement*
hence sorption layer thickness (s) =	*0*	*mm*
hence diffusion layer thickness (d) =	*40*	*mm*
Assume concrete density (W_t) =	2400	kg/m^3
hence time to reach activation is	54	yrs
Calculate Propogation Time (T_1)		
Bar Diameter	20	mm
Spalling or structural Fail	Spall Life	
Size Of Element	Precast Tunnel Rings	
hence length of cathode =	1000	cm
hence length of anode =	1000	cm
hence propogation time is	20	yrs
Hence Life Of The Structure =	**74**	**yrs**

Fig 2 - Life For 10% Silica Fume

Exposure	Tunnel - Reabsorption	
temperature (T) =	20	*°C*
hence surface chloride level (C_o) =	*3*	*wt%cement*
hence wet time for a spalsh (W_t) =	*0*	*min*
hence potential difference (v) =	*200*	*mv*
Concrete Quality		
w/c ratio (w)	0.35	
Silica fume content (f)	10	% by wt of cement
hence sorptivity (S) =	*0.06*	*mm/min$^{0.5}$*
hence diffusion coefficient (D_c)=	*6.2E-09*	*cm/sec^2* at 20C
hence diffusion coefficient (D_c)=	*6.2E-09*	*cm/sec^2* at given temp
hence resistivity (R)=	*49007*	*ohm cm*
Assume the concrete voids ratio (v)=	*0.1*	
Calculate Time To Activation (T_0)		
Cement Content (C_e)	400	kg/m^3
Cover (c)	40	mm
Assume critical chloride level (C_c) =	*0.4*	*wt % cement*
hence sorption layer thickness (s) =	*0*	*mm*
hence diffusion layer thickness (d) =	*40*	*mm*
Assume concrete density (W_t) =	2400	kg/m^3
hence time to reach activation is	72	yrs
Calculate Propogation Time (T_1)		
Bar Diameter	20	mm
Spalling or structural Fail	Spall Life	
Size Of Element	Precast Tunnel Rings	
hence length of cathode =	1000	cm
hence length of anode =	1000	cm
hence propogation time is	53	yrs
Hence Life Of The Structure =	**125**	**yrs**

Durability Considerations

Durability of the MRT tunnel lining was a major consideration as other precast linings have required major repairs after only a few years. Calculations on the life of the tunnel with 5% silica fume (fig 1) and very low water:cement ratios showed that the design life of 100years would not be met and that coating was essential. With 10% silica fume (fig 2) the coating would not be necessary. The durability concern was accentuated in the analysis of all potential deterioration mechanisms which showed that the internal surface of the lining was at risk from ingress from contaminants from leaking joints and cracks. No coating was planned for the internal face and the design model predicted a life of only 60-80 years with 5% silica fume. By comparison 10% silica fume (fig 2) gave a life of 110-140years

Consequently, tests were undertaken at CSIRO's fire testing facility in Sydney to determine wether

- increasing the dosage of silica fume increased the risk of explosive spalling
- if the risk were increased wether it could be eliminated by the use of nylon fibres

Table 2 – Mix Designs Used for the Fire Test Panels

Mix	1	2	3	4
Cement (kg/m^3)	485	370	370	420
Silica Fume (kg/m^3)	-	40	40	25
Binder (kg/m^3)	485	410	410	445
Eq, Binder e=2.85 (kg/m^3)	485	484	484	491
Water (kg/m^3)	170	150	150	160
Water/binder	0.35	0.37	0.37	0.34
Nycon (kg/m^3)	-	0.6	-	-
Coarse (kg/m^3)	1060	1070	1070	1070
Fine (kg/m^3)	610	720	720	710
Water reducing retarder	1940	1850	1850	2100
Slump (mm)	40	40	40	50

The Synthetic Fibre

Nylon fiber's were selected as

- synthetic fibre has been proven to eliminate explosive spalling in refractories
- having determined that synthetic fibres would be used nylon appeared to provide several advantages
  - polypropylene repels water while nylon absorbs water. Hence, nylon provides a good bond without requiring a mechanical key. This leads to a better performance at a lower dosage making nylon more economical in terms of achieving two items of interest in the overall design of a segment:
    - capacity to reduce the need for early age curing
    - impact resistance during handling
  - the nylon fibre does not have a 'hairy finish'. A hairy finish could have affected the sealing of the segments

Sample Preparation

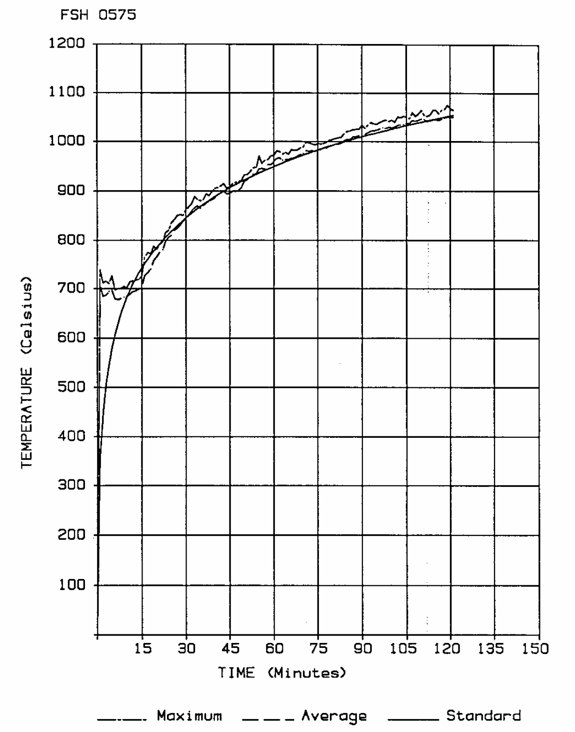
Timber moulds 1.1mx4.5mx.25m were prepared.

Reinforcement comprising Y16 bars at 200mm centers in both faces with 40mm cover was placed using steel bar chairs.

All concrete was produced by CSR Readymix at there Artarmon plant.

Mix 4 (table 2) was selected as the starting point as it is similar to that likely to be used on the MTR. Mix 1 is a mix of similar strength but without silica fume. The objective was to determine if an OPC mix exhibited similar characteristics to the silica fume mixes. Mix 3 is the 10% silica fume alternative with the water binder ratio maintained. The cementitious content has been reduced due to the efficiency (assumed conservatively at 2.85) of the silica fume for strength. Mix 2 is the same as mix 3 except that Nycon Nylon fibres are included.

Figure 3 – Heating Curve Followed for Slab Tests



After placing the concrete was cured for 24 hours and then stored in the open until 28 days when they were tested.

Fire Testing

CSIRO reported their findings for the fire test conducted on 8 May 1998 under their test number FS3017/1634. The heating conditions used were as specified in clause 2.9 of Australian Standard 1530.41997, "Fire-Resistance Tests of Elements of Building Construction" & British Standard 476 Part 20 & 22-1987 "Fire Tests on Building Materials and Structures" with no departures from these requirements.

The specimens comprised four 4500 mm long x 1100 mm wide x 250 mm thick, concrete slabs. The overall dimensions of the slab system were 5000 mm long and 4500 mm wide to sit on top the furnace opening. The concrete slabs spanned 3660 mm, were unsupported on the edges and simply supported on the ends.

The furnace had a nominal opening of 4570 mm x 3660 mm for attachment of horizontal specimens. The furnace was lined with refractory bricks and materials with the thermal properties as specified in AS 1530.4-1997 and was heated by combustion of a mixture of natural gas and air.

The temperature in the furnace chamber was measured by nine type K, 3 mm diameter, 310 stainless steel Mineral Insulated Metal Sheathed (MIMS) thermocouples, Each thermocouple was housed in high-nickel steel tubes opened at the exposed end. Figure 1 shows the standard curves of temperature versus time for heating the furnace chamber and the actual curves of average and maximum temperature versus time recorded during the heating period.

Table 3 –Observations During The Fire Test

Time (mins)	CSIRO Observation
10	General spalling sounds are audible from the slabs.
15	It appears that exposed sides of slabs 1,3 & 4 are spalling. Moisture is forming along the exposed edges of all the slabs.
20	Moisture is forming on top of slab 2.
25	Exposed face of slab 3 appears to be spalling the most, while the underside of slab 2 appears to be unaffected.
40	Spalling sounds appear to have stopped.
45	Moisture patches are appearing on top of slabs 1 & 4.
60	No apparent change to the specimens.
120	Test terminated. Examination of the specimens after the termination of the test showed slab 2 had hair cracks but only otherwise substantially unaffected. Slabs 1, 3 & 4 showed significant spelling.

The temperature of the test area was 24'C at the commencement of the test. The test was terminated at 120 minutes as requested by the sponsor. The furnace pressure was measured by a differential low-pressure transducer with a range of ± 50 Pa. The primary measurement system comprised a multiple-channel datalogger scanning at one minute intervals during the test. After each scan the information was stored on magnetic disc by the computer controller. The heating curve followed is shown in figure 3.

The observations made during the fire-resistance test are shown in table 3 and photographs are shown in figs 4-11.

Figure 4 – Exposed Face Of Slab 1On Completion

Figure 5 – Exposed Face Of Slab 2 On Completion

Figure 6 – Exposed Face Of Slab 3 On Completion

Figure 7 – Exposed Face Of Slab 4 On Completion

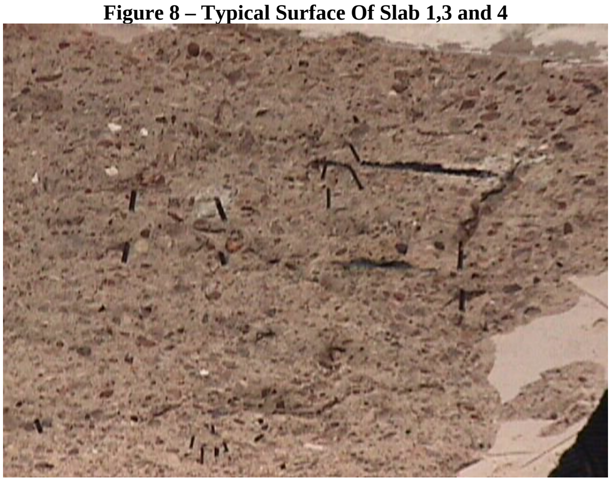


Figure 8 – Typical Surface Of Slab 1,3 and 4


Figure 9– Typical Surface Of Slab 1,3 and 4


Figure 10 – Surface Of Slab 2


Figure 11 – 45minutes Into Test

Discussion

The slabs were tested at 28 days to ensure that moisture was still locked into the concrete. This is somewhat abnormal in fire testing as concrete panels normally submitted for a fire rating test are allowed to dry totally to ensure the potential for explosive spalling is eliminated.

For internal walls of buildings it can be argued that the concrete will dry out and as there is no free water it is appropriate to test dry panels. For exposed concrete, and particularly tunnels where moisture will be available from the buried face, it is more appropriate to test a panel with moisture. The results shown here indicate that 28 day testing is appropriate.

The testing showed no difference in the performance of 0, 5 and 10% silica fume concrete in terms of explosive spalling, they all failed badly. This fact gives serious concern for the performance of concrete in a fire in a tunnel. The Nycon fibres proved extremely effective in eliminating the risk of explosive spalling. Only a few aggregate popouts occurred. In addition to providing protection to this type of failure the fibres will provide resistance to edge damage during handling and plastic crack control.

The concrete proposed (10% silica fume, w/c=0.35) will become impenetrable at a very early age and curing past 24 hours would be pointless. The Nycon fibres will prevent early age plastic cracking while the low cementitious content will reduce the possibility of thermal cracking. To provide a total durability of the internal and external face while eliminating explosive spalling it is proposed that the following solution is adopted:

- 10% silica fume
- w/c 0.35
- binder content 410kg/m^3
- Nycon nylon fibres 0.6kg/m^3

ANCON BETON'S INTERIM REPORT ON

CORES FROM FIRE TESTED CONCRETE PANELS

5th JUNE 1998

Twelve cores were taken from 4 concrete panels after the panels were subjected to fire testing by CSIRO in accordance with AS1530.4-1997, "Fire Resistance Tests of Elements of Building Construction" & BS 476, Fire Tests on Building Materials and Structures, Part 20 & 22-1987.

The panels were made from different concrete with the significant differences as follows:

Panel 1 Cement only, no silica fume (SF) or fibres.
Panel 4 5% silica fume as cement replacement.
Panel 3 10% silica fume as cement replacement.
Panel 2 10% silica fume as cement replacement and 0.6 kg/m^3 of Nycon nylon fibres.

The cores were taken as follows:

1 # full depth core from each panel (4 cores total).
2 # half depth cores taken from the rear side (away from the fire) of each panel (8 cores total).

VISUAL INSPECTION

The full depth cores were inspected visually on the 4th June 1998 and found to be obviously fire affected on one end.

The full depth cores from panels 1, 3 and 4 were similar in appearance with: a complete loss of the fire affected surface, crumbling concrete to a depth of 20 to 30 mm, colour changes to buff, dark grey and light grey/pink at certain depths, and large longitudinal cracking to a considerable depth

The full depth core from panel 2 had a very different appearance with the fire affected surface still intact, fire damage and heat induced colour changes at much shallower depths, and much shallower cracking compared to the other cores.

The presence of intact fibres in cores from panel 2 at such a close distance from the fire-affected surface (58 mm) indicates that:

1. The temperature developed in the concrete at the location of the fibre was below the melting point of the fibre (about 220^{o}C).
2. The first colour change was deeper than the fibre, suggesting that the colour change occurred at less than 300 ^{o}C, or more likely, that the voids where the fibres are still intact were at a lower temperature than the surrounding concrete.
3. The fibres reduced the incidence of cracking and prevented longitudinal cracks from forming.

One half depth core from panel 2 was split for inspection. The broken face was seen to be entirely intact and unaffected by heat of fire with the fibres still intact and no damage to the concrete or fibres.

The results of the inspection are given in table 1.

GRAPH OF CHANGES

The attached graph shows the depth of the changes for colour, visible fibres and appearance of large cracks for each of the full depth cores. The graph shows:

There is no significant change in depth of the colour changes in the cores (and hence progression of elevated temperatures through the concrete) with varying contents of silica fume from 0% to 10%.
There is a significant variation in depth of cracks between specimens, although this may be due to the random nature of the cracking so that one core from each panel may not detect the full cracking pattern.
Panel 2 containing Nycon fibres had significantly lower depths of cracking, and less effect from heat transmission through the concrete as evidenced by the shallower depths of colour changes.

CSIRO REPORT

Photographs in the report showed that water pooled on the rear of panel 2 but not on the other panels.

The panels were all 28 days old when tested and so would have contained at least 5% free moisture.

It is considered that the moisture in panels 1,3 and 4 may have escaped through the large cracks that formed. Since the cracks in panel 2 did not penetrate as deeply across the panel, the moisture may not have been able to escape in this way and was forced to permeate through the body of the concrete to pool on the top surface.

CONSIDERATIONS

1. The concrete from panel 2 showed a resistance to fire that was significantly superior to the non-fibre reinforced concretes.

2. The concrete at and near to the fire-affected surface was still intact, although fire damaged in panel 2.
3. The depth of severely damaged concrete was much less in panel 2.
4. The core from panel 2 showed no longitudinal cracking, with the large cracks confined to the near surface area.

FURTHER WORK

Fire and heat dramatically reduce the strength of concrete. The differences that are visible in the cores should be reflected in the degree of strength loss in the concrete at different depths.

I therefore recommend that more cores are taken and sectioned for compressive strength testing. The cores should be 75 mm diameter in accordance with the Australian Standards, and can be cut into two sections, each about 100 mm in length. The core section nearest the fire should have reduced strength, and will show any differences in strength loss between the different concretes. The core section furthest from the fire should be more like the full strength of the concrete, but again should reflect any differences in strength loss between the different concretes.

INSPECTION RESULTS

Panel No.	Mix Details	Distance from fire affected face	Feature
1	Cement only	180 mm	Large longitudinal cracks
		85 mm	Colour change to light grey/pink, occurs between 300°C and 600°C
		55 mm	Colour change to dark grey, up to 900 °C
		25 mm	Colour change to buff & crumbling, above 900 °C
2	10% SF + 0.6 kg Nycon fibre	83 mm	Colour change to light grey/pink, occurs between 300°C and 600°C
		72 mm	Large cracks
		65 mm	Nycon fibre visible in voids
		58 mm	Nycon fibre visible in voids
		50 mm	Colour change to dark grey, up to 900 °C
		12 mm	Colour change to buff & some crumbling, above 900 °C
		0 mm	Surface still intact although some crumbling
3	10% SF	220 mm	Large longitudinal cracks
		85 mm	Colour change to light grey/pink, occurs between 300°C and 600°C
		55 mm	Colour change to dark grey, up to 900 °C
		30 mm	Colour change to buff & crumbling, above 900 °C
4	5% SF	95 mm	Large longitudinal cracks
		70 mm	Colour change to light grey/pink, occurs between 300°C and 600°C
		55 mm	Colour change to dark grey, up to 900 °C
		20 mm	Colour change to buff & crumbling, above 900 °C

Compressive strength Of Cores
Testrite certificate no 41210

Panel 1	44.5Mpa
Panel 2	49MPa
Panel 3	50MPa
Panel 4	58MPa