Effects of polypropylene fibres in concrete: Microstructure after fire testing and chloride migration

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Explosive spalling of pieces of concrete from the heated surface is considered to be the most dangerous effect of damage of concrete subjected to intense fire attack, especially when it occurs in restricted areas such as underground tunnels. Recent investigations have revealed that the amount of explosive spalling and the extent of cracking can considerably be reduced by use of suitable amount of polypropylene fibres. However, little attention has been given to exactly how the fibres behave in the matrix of the concrete when exposed to fire. A good insight into the behaviour of the fibres when applied in concrete, especially when subjected to fire, can help optimise their use to reduce explosive spalling. This paper deals with a case study, in which an integrated microscopic method consisting of stereomicroscopy and polarising and fluorescent microscopy were used to assess the effectiveness of the pp-fibres in reducing explosive spalling in concrete elements subjected to fire attack. Rapid Chloride Migration test was also performed on standard specimens to establish whether the presence of the fibres might adversely affect the permeability and durability of the elements.

Key words: Spalling, polypropylene fibres, microscopy, microstructure, durability

1 Introduction

1.1 Background

Explosive spalling of pieces of concrete from the heated surface is considered to be the most dangerous effects of damage of concrete subjected to intense fire attack, especially when it occurs in restricted areas such as underground tunnels. Several recent investigations have revealed that the amount of explosive spalling and to some extent, the loss of strength and the extent of cracking, can considerably be reduced by use of suitable amount of polypropylene fibres, pp-fibres [Hannant 1998, Tatnall 2002, Segre et al. 1998]. However, little attention has been given to exactly how the fibres behave in the internal structure of the concrete when exposed to intense fire and the fundamental mechanisms that lead to the reduction in explosive spalling. A good insight and understanding into the behaviour of the fibres when applied in concrete subjected to fire can help optimise their use to reduce explosive spalling, which arises mainly from the vapour pressure build-up mechanism. This applies especially to their distribution in the cement paste matrix, the development of the channels after they have melted and evaporated and their interactions with microcracks in the cement matrix. At the same time the fibres should not affect the concrete's resistance to aggressive attacks, for example, the ingress of chlorides. Research work shows that the use of various microscopic methods, such as stereomicroscopy and a combination of Polarizing and Fluorescent Microscopy (PFM) are effective tools for acquiring valuable information about concrete attacked by fire, including those containing pp-fibres. In recent years, this integrated microscopic method has been used to characterize the microstructure of various cement paste matrices and to help understand the behaviour of concrete containing pp-fibres exposed to elevated temperatures and subsequent cooling [Larbi and Nijland 2001, Larbi and Siemes 2000]. The effectiveness of the integrated microscopic method in performing such assessments lies not only in its ability to identify various mineralogical phases in concrete, but also on its value in revealing structures that are not visible to the naked eye. This is quite unique and vital in understanding the interactions between the cement paste matrix and the inserts.

This paper deals with a case study, in which an integrated microscopic method consisting of stereomicroscopy and PFM, was used to assess the effectiveness of the pp-fibres in reducing explosive spalling in concrete elements subjected to fire attack. To establish whether the presence of pp-fibres might have adversely affected the permeability and durability of the elements, Rapid Chloride Migration (RCM) testing was also performed on standard specimens.

1.2 Spalling of concrete exposed to fire

Spalling can be described as the detachment of layers or pieces of concrete from the surface of a structural element when it is exposed to the high and rapidly rising temperatures experienced in fires. Research work shows that there are two types of spalling due to fire: gradual spalling and sudden or explosive spalling [Bayasi and Dhaheri 2002, Segre et al. 1998]. Gradual spalling involves the release and falling-off of the exterior concrete surface resulting in non-violent dislodging of the concrete. This may occur in concretes where there is a slow rate of rise of temperature in the concrete due to the fire attack.

With respect to explosive spalling, field surveys and studies show that this occurs when pieces of the exterior concrete at high pressure are suddenly, forcibly and violently dislodged from the surface, with an 'explosive' effect, due to rapid heat-rise and build-up of vapour pressure. The conventional theory of explosive spalling is that it is mainly caused by the build-up of water vapour pressure in concrete during fire. If the concrete is not quite permeable, water vapour formed within the concrete during heating will not be able to dissipate or migrate away quickly from the heat out of the concrete and pressure is formed. This usually occurs when there is a rapid temperature rise, as occurs in hydrocarbon-fuelled fires. As the temperature of the concrete increases, the moisture in the concrete pores evaporates and builds up pressure. When that pressure exceeds the tensile strength of the concrete, explosive spalling occurs. This is the more dangerous form of spalling. In explosive spalling, which is common in high-performance concrete, it has been proposed that the intensity of explosion is governed by several factors, including the age of the concrete, strength, compactness of the cement paste matrix, which in turn depends on the water-binder ratio, the type of aggregate, presence of fibres, the vapour pressure mechanism, which in turn, is governed by the moisture content of the concrete and the rate at which the concrete is heated [Hannant 1998, Tatnall 2002, Segre et al. 1998].

*1.3 **Theory underlying the positive effects of use of pp-fibres to reduce spalling***

One of the well-known methods of reducing the risk of explosive spalling is the addition of pp-fibres to the concrete mix. This approach works on the basis that the pp-fibres have different thermal characteristics from those of normal concrete. The mechanism underlying the positive effects of application of pp-fibres is that, when concrete containing pp-fibres is exposed to elevated temperatures or to fire, the pp-fibres undergo two main effects, which ultimately reduce damage due to explosive spalling [Bayasi and Dhaheri 2002, Hannant 1998, Tatnall 2002, Segre et al. 1998, Kalifa et. al 2000].

First, of all, the fibres expand at a different rate than the matrix, causing small fissures or openings to be formed between the cement paste matrix and the fibres. Research work shows that these fissures are enough to allow some relief of the vapour pressure that builds up in the pores of the concrete. Secondly, as the heating continues and the temperature of the fibres reaches the range of 165-171°C, the fibres melt. From 360°C, the fibres evaporate. Disappearance of the fibres provides passageways or channels along which water vapour can dissipate, so avoiding build-up of pressure. These two effects enhance the relief of the stresses that are suddenly developed by the vapour pressure build-up, which subsequently reduce explosive spalling.

2 Case study

2.1 Introduction

This section deals with a case study in which various methods, including an integrated optical microscopy and RCM test [NT Build 492 1999] were used to study the fire resistance and durability of polypropylene fibre-reinforced concrete elements. The study presented in this paper was performed for two primary reasons:

- to supplement a quality control investigation of the fire resistance of two concrete elements prepared with 1 and 3 kg/m^3 pp-fibres;
- to assess the effectiveness of the pp-fibres in reducing the risk of damage due to spalling;
- to check for any negative effect on chloride penetration resistance.

The concrete elements were designed for use as protective linings in a railway tunnel in The Netherlands. As one of the criteria for application of the elements, it was required to determine their resistance against attack by fire. In the light of this, the total study was phased-out as follows:

a. design, production and testing of the fire resistance of the two pp-fibre-reinforced elements;
b. characterisation of the microstructure of the fire-attacked elements and assessment of the effectiveness of the pp-fibres in reducing the risk of damage due to spalling;
c. assessing the permeability and durability of the elements by RCM test on standard specimens.

a. Testing of fire resistance

The resistance of the elements to fire was tested by TNO Centre for Fire Research using a standard testing method according to the RWS-curve. Details of the test have already been described elsewhere and shall not be presented in this paper [Both 2000].

b. Assessment of effectiveness of fibres in reducing damage to spalling

After the fire test, the effectiveness of the fibres in reducing damage due to explosive spalling was assessed using an integrated method consisting of visual examination of cores drilled from the spalled surface of the elements, stereomicroscopy and PFM. The PFM assessment involved microscopic examination of 25 µm thin sections of specimens removed from the heat-affected cores and included the following:

- examination of the presence and distribution of the fibres in the cement paste matrix;

- interactions of the fibres with the cement paste matrix, especially interactions with crystalline hydration products, voids and microcracks;
- extent of melting, presence of channels and their relationship with microcracks;
- changes in the overall microstructure of the cement paste as a result of the heat changes, including changes in the capillary porosity, de-bonding of cement paste from aggregate particles, microcracking in aggregate and cement paste and compactness of cement paste.

Other aspects evaluated included the extent of alteration of heated material and the material loss measured from the fire-exposed surface due to spalling.

c. Durability testing

The purpose of this test was to establish whether the presence of pp-fibres would adversely affect the permeability and durability of the concrete. This aspect was assessed by means of RCM testing [NT Build 492 1999] performed on standard specimens cast with or without polypropylene fibres, but not subjected to the fire test.

*2.2 **Test procedure and results***

a. Concrete elements

Two concrete elements were cast for the tests. Each measured about 4850 mm x 2200 mm and with a nominal thickness of about 420 mm. The concrete used, which was prepared by a local concrete manufacturing company, was designed to meet the Dutch specifications. The aggregates used were river gravel and sand with a maximum aggregate size of 16 mm. The binder consisted of a mixture of CEM I 52.5 R and pulverised fuel ash. The age of the elements at the time of fire testing was one month. A summary of the concrete composition is given in Table 1. An overview of the elements after the fire test showing the location where the cores were taken and damage caused by the fire is shown in Figure 1. In all cases, the polypropylene fibres used consisted of monofilament type, from the firm Confiber. Each had a nominal length of 12 mm and a cross-section of 18 µm.

b. Concrete cores

Following the fire testing, nine cores were drilled from each element for further assessment by means of the integrated microscopic method. An additional core was drilled each from two concrete cubes that were not subjected to the fire test, but used as reference specimens. All the cores had a diameter of about 100 mm and lengths ranging from 390 to 420 mm.

After sampling, the cores were examined with the aid of a stereomicroscope for evidence and characteristics of damage due to fire.

2.3 *Visual examination of cores*

Visual examination of samples, often aided with stereomicroscopy, is usually the first step of microscopically diagnosing the extent of damage in concrete cores. This phase of the study is also used to obtain first-hand information about the materials in order to assist in the selection of specimens for further examination by means of PFM. An overview of some of the cores is shown in Figure 2.

Table 1: Concrete composition

	Sample [kg.m^{-3}]			
	R0	R2	A	B
CEM I 52.5	310			
Fuel ash	80			
Admixture	1.5 % FM and 0.5 % BV			
Water-binder ratio	0.45			
Sand: 0-2 mm and 0-8 mm	757 and 297			
Gravel: 8-16 mm	833			
Polypropylene fibres	0*	2	1	3
28-day compressive strength, Nmm^{-2}	54.0 ± 0.4			

** The elements were coded as follows:*

R0 : reference sample, concrete cubes without pp-fibres

R2 : reference sample, concrete cubes with 2 kg.m^{-2} pp-fibres

A : fire tested concrete element with 1 kg.m^{-2} pp-fibres

B : fire tested concrete element with 3 kg.m^{-2} pp-fibres

a. Overview *b. Details*

Figure 1: Portion of one of the tested concrete elements after the fire test showing some of the locations where the cores were removed for further analysis and damage due to spalling

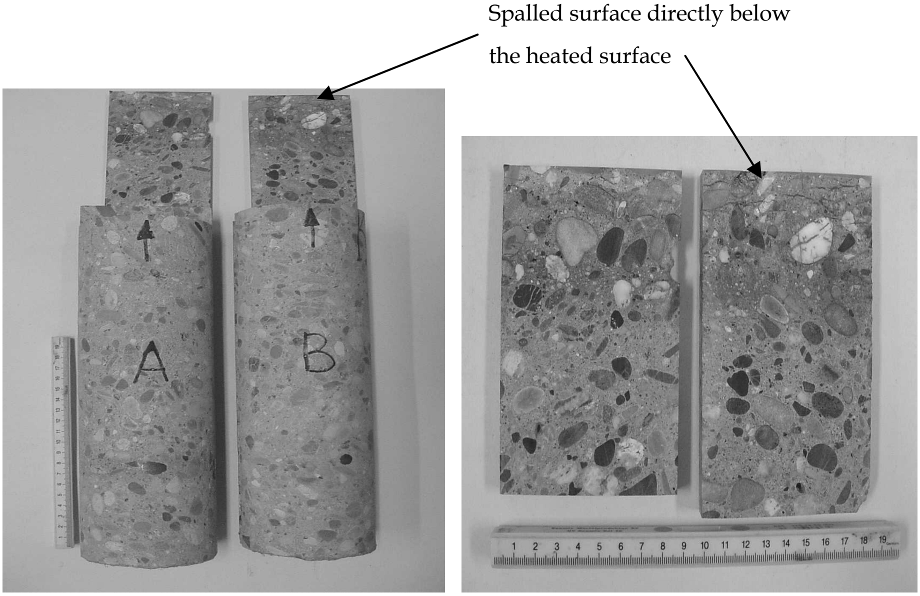
Figure 2: Overview of some of the cores removed from the two concrete elements for the microscopic studies showing the spalled surfaces and colour changes caused by fire heating

Directly below the spalled surface, that is, the fire-exposed surface, was a whitish-grey zone, characterised by loss of bonding of the cement paste to the coarse aggregate particles and severe microcracking of the cement paste and the coarse aggregate particles. Around most of the coarse aggregate particles, which consisted essentially of quartzite, chert, sandstone and quartz, most of the cracks were radial, often crossing other cracks from adjacent particles, indicating SiO_2 phase change and reflecting that the zone in question had experienced temperatures exceeding 573°C.

Adjacent to this zone was a thin pink zone, varying in thickness between 0 and 10 mm and showing a less severe form of physical deterioration. This is apparently the zone affected by oxidation of various Fe-hydroxides to hematite, resulting in the pink colour. Beyond this zone, the colour of the concrete, the amount of cracks and the compatibility of the concrete were quite similar to those of the reference, not-heated concrete core. A number of these features are clearly shown on the polished specimens in Figure 3.

2.4 ***FMA analysis***

Following visual inspection of the cores, one polished section and two thin sections were prepared from each core and examined with the aid of UV-light, in the case of the polished sections, and a combination of a polarising and fluorescent microscope, in the case of the thin sections. FMA (fluorescent macroscopic analysis [Polder and Larbi 1996] was performed to determine the intensity and depth of microcracking of the concrete and its effect on the integrity of the concrete as whole.



a. approximate length of cores *b. polished specimens*

Figure 3: Overview of two cores showing areas where specimens were removed for further microscopic studies

Figure 4 shows FMA-photomicrographs of the development of cracks in the fire tested samples A and B. In both cases the development of cracks can be related to the fire attack. The cracks developed are mainly sub-vertical to the surface of exposure, but there are also cracks that are oriented more or less parallel to the fire-exposed surface of the elements. At various places, this damage is associated with scaling, de-bonding of the cement paste from the aggregate and weakening or loss of cohesion of the cement paste matrix. These features are typical of attack due to fire [Larbi and Nijland 2001, Larbi and Siemes 2000, Nijland and Larbi 2002]. An overview of the extent and depth of attack in each of the two cores as a result of the fire testing is shown in Table 2.

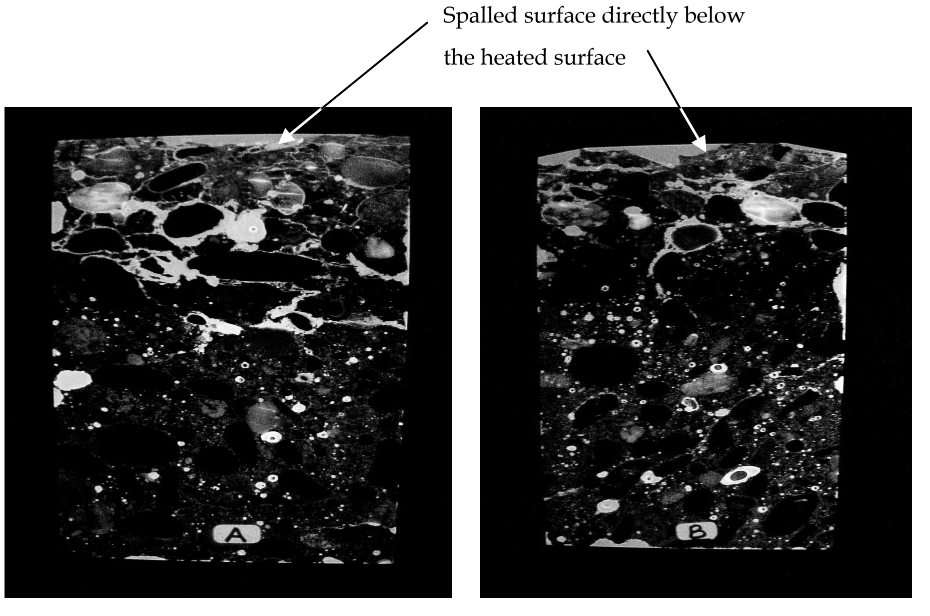
2.5 ***PFM analysis***

PFM analysis was focused on examination of thin sections prepared from concrete between the spalled surfaces down to a depth of about 100 mm. The aim of the study was to characterise the microstructure of the various cement paste matrices with and without the pp-fibres in order to understand the behaviour of fibres when exposed to high temperatures. PFM aids in revealing various phase changes of the cement paste, especially

Table 2: Overview of the depth of attack due to fire testing in the cores examined

Code	Extent of cracking in specimens	Cohesiveness of concrete	Extent of attack	Depth of attack in the specimen* (mm)
R0	0	Good	0	0
R2	0	Good	0	0
A	0-50 mm - large 50-160 mm - small	0-50 mm is poor 50-160 mm is good	0-50 mm is large 50-80 mm is small	50
B	0-30 mm - large 30-150 mm is small	0-30 mm is poor 30-150 mm is good	0-30 mm is large 30-50 mm is small	30

** The spalled portion was not considered in the evaluation. R0 and R2 are reference, non-fire tested samples. A and B are fire-tested samples.*



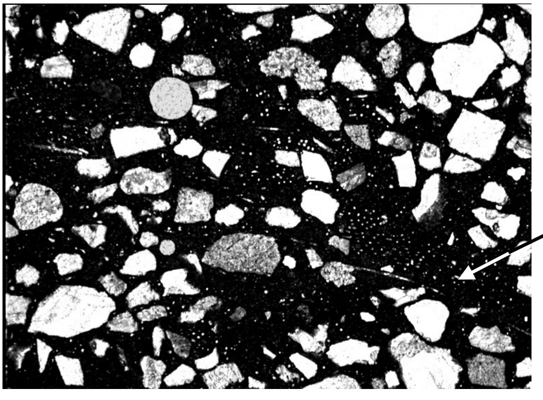
a. specimen removed from sample A *b. specimen removed from sample B*

Figure 4: FMA-photomicrographs showing the presence of cracks in the specimens removed from samples A and B. Magnification: 6x

the disappearance of phases like ettringite, portlandite, calcium carbonate and the calcium silicate hydrates and secondary phases formed. Phase changes could be used to identify series of isograds as a function of depth from the surface of the concrete [Larbi and Nijland 2001, Larbi and Siemes 2000, Nijland and Larbi 2002].

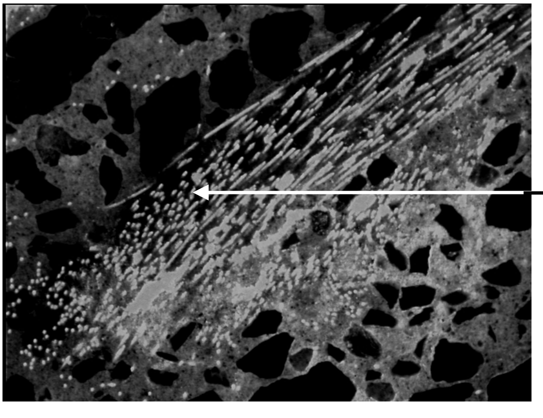
a. Distribution of pp-fibres

Figure 5 shows a photomicrograph of a thin section of the reference element, R2, with 2 kg.m^{-2} of pp-fibres, showing the distribution of the pp-fibres, as small 'dots' (cut through cross-sections of the fibres), in the cement paste matrix. The micrograph shows that the distribution is not uniform in the cement paste. This also applies to the photomicrograph in Figure 6, which was taken from a thin section specimen of a core removed from element, B, containing 3 kg.m^{-2} pp-fibres and subjected to intense heating in the fire test. The small light-green spots in the fluorescent micrographs in Figures 6 and 7 are the channels developed after the pp-fibres had melted and evaporated.



pp-fibres in cement matrix
not subjected to heating

Figure 5: PFM-microphotograph of reference element, R2, containing 2 kg.m^{-2} pp-fibres showing distribution of pp-fibres in cement paste matrix. Concrete was not exposed to fire. View is 2.7 mm x 1.8 mm.

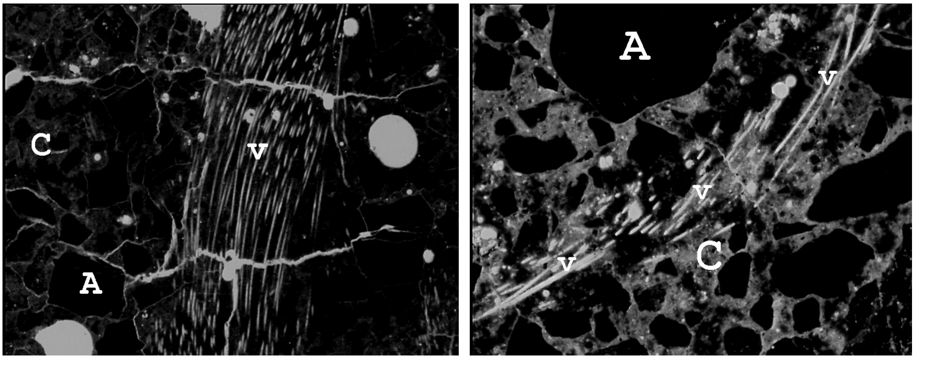


Channels created in cement
matrix due to melting and
evaporation of pp-fibres

Figure 6: PFM-microphotograph taken at about 20 mm from spalled surface element, B, containing 3 kg.m^{-2} pp-fibres. View is 2.7 mm x 1.8 mm.

b. Bridging of microcracks in cement paste

Figure 7 shows two photomicrographs taken at about 20 mm from spalled surface of the fire tested elements A and B, showing development of channels and bridging-up of microcracks in cement paste matrix. In all micrographs, the light-green spots or short lines are voids or channels developed where the pp-fibres had melted and evaporated, which clearly shows that the temperature here had exceeded 171°C (melting) and possibly 360°C (evaporation) of fibres. These effects are known to reduce the risk of damage due to explosive spalling [Bayasi and Dhaheri 2002, Hannant 1998, Tatnall 2002, Segre et al. 1998 and Kalifa et al. 2000]. The fibres appear to have bridged-up the microcracks developed in the cement paste matrix. It appears further that not all the fibres had evaporated. The photos also show that the fire had caused severe cracking in the top portion (20-55 mm) of the concrete cores. The bottom part of the specimens was found to be void of visible cracks as a result of the fire activity. Only few, fine microcracks were found in the cement paste matrix, possibly due to other effects such as chemical shrinkage from hydration or post-heating shrinkage arising from cooling. Similar features were observed in the thin sections of the other cores. Further observations revealed intense microcracking of cement paste matrix and coarse aggregate particles directly below the spalled surface and deeper, circa 50 mm. Also, the capillary porosity of the cement paste matrix in the area directly below the spalled surface was found to be adversely affected as a result of the intense heating of the elements: it had increased considerably compared to that of the reference specimens. This effect is clearly the result of loss of physically bound water in the cement paste matrix



a. element A, containing 1 kg.m^{-2} pp-fibres *b. element B, containing 3 kg.m^{-2} pp-fibres*

Figure 7: PFM-photomicrographs taken at about 20 mm from spalled surface of both elements showing development of channels and microcracks in cement paste. A = aggregate; C = cement paste matrix; v = pp-fibres.

due to the heating [Larbi and Nijland 2001, Larbi and Siemes 2000, Nijland and Larbi 2002]. A schematic diagram representing features observed is given in Figure 8.

2.6 *RCM testing and results*

From the elements cast for the fire testing, separate cubes were cast from which cores were taken for additional tests. Results are reported here for rapid chloride migration test (RCM). This test is aimed at determining the resistance of concrete against chloride ion penetration. Chloride ions are forced through a specimen placed between solutions of sodium chloride (cathodic chamber) and sodium hydroxide (anodic chamber) by imposing an external voltage of 12 to 60 V between the chambers. The voltage strongly accelerates the penetration rate of chloride ions. After 24 to 72 hours, the specimen is removed from the cell and split along its central axis (parallel to the direction of the current). The split surfaces are sprayed with silver nitrate solution to make the chloride penetration front visible. The migration coefficient is then calculated from the voltage, the time, the cathodic chloride concentration and the depth of the chloride penetration front [NT Build 492 1999]. The result is interpreted as a measure of chloride diffusion in the concrete, which can be used to compare concrete compositions or as input for service life design calculations [DuraCrete 2000].

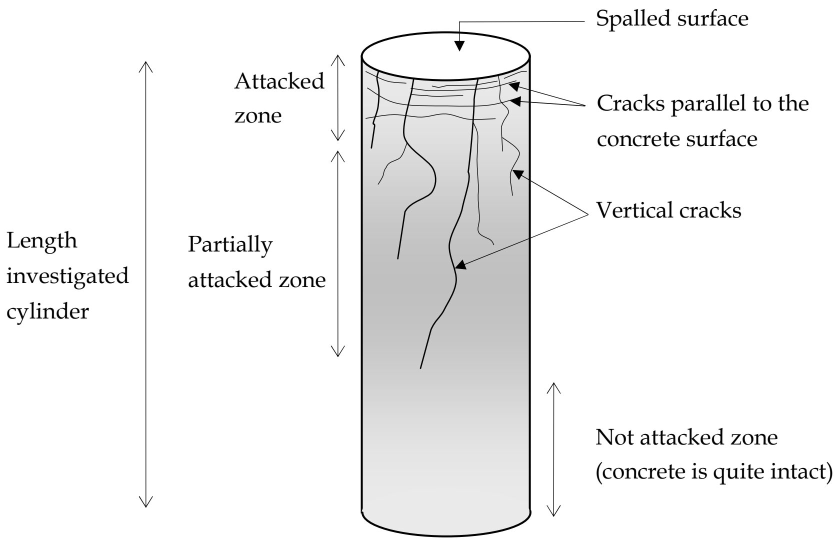


Figure 8: Schematic representation of the microscopic features observed from PFM analysis of thin section specimens

The concrete had the composition as reported before in Table 1, however, with fibre contents of 0, 1, 2 and 3 kg/m^3. Cores removed from concrete cubes with a diameter of 100 mm were sawn into 50 mm thick disk specimens and stored in lime-water at 20°C until tested. Three disks of each composition were tested at 28 days; three at 90 days and three at 365 days age. Variation between specimens was small. Table 3 reports the mean RCM results.

Table 3: Chloride migration coefficients of pp-fibre concrete at three ages (mean of three specimens)

Mix	pp-fibre content (kg/m^3)	RCM (*10^{-12} m^2/s) at various ages		
		28 days	90 days	365 days
R0	0	6.5	2.4	1.0
R1	1	7.6	2.7	1.0
R2	2	7.4	2.8	0.9
R3	3	7.9	3.0	1.1

The migration coefficients reported show that differences between the four mixes are small. At first sight, mix R0 (without pp-fibres) might be seen as to have a slightly lower value than the other three (containing pp-fibres) at 28 and 90 days. However, the differences are small with respect to the scatter in RCM results, for which a coefficient of variation is usually found of 10 - 25% (Tang and Sørensen 2001). Scatter in the present results was on the lower side of this range, suggesting the concrete had a good homogeneity. Any differences between mixes are probably due to small differences in compaction, which may be related to the effect of the fibres on workability. However, if the fibres would have a significant effect on the concrete's resistance against chloride penetration, it should have been clearly visible for the higher fibre contents. RCM values should have increased strongly going from mix R0 to R3. As this is clearly not the case, there is no significant effect of the pp-fibres on the chloride penetration resistance up to 3 kg of pp-fibres per m^3 in the investigated concrete.

Another observation is that the RCM value of the mixes decreases with exposure time. This is normal and is found for all types of concrete, with a stronger decrease for blast furnace slag cement and in particular with binders containing fly ash, as compared to pure Portland cement concrete. In fact, these four mixes show a time dependency that is very similar to a comparable Portland plus fly ash mix without fibres.

3 Discussion

3.1 Spalling

The results of the present study show that addition of 1 kg.m^{-2} and 3 kg.m^{-2} pp-fibres respectively to the concrete tunnel lining elements A and B could not prevent explosive spalling from occurring when subjected to fire attack. In both elements A and B spalling did occur.

3.2 Development of channels

The integrated microscopic study shows that in both elements A and B, which were exposed to intense heating in a fire test, there is clear evidence of disappearance of the polypropylene fibres. This has resulted in the development of channels in the cement paste matrix up to a depth of about 55 mm from the spalled surface, apparently due to the melting and evaporation of the pp-fibres as explained elsewhere [Hannant 1998, Tatnall 2002, Segre et al. 1998], suggesting that in this zone, the temperature of the cement paste matrix had exceeded or at least reached the melting temperature (171°C) and possibly the evaporating temperature (360°C) of the pp-fibres. The study also shows that the applied integrated microscopic method is quite useful in performing such a study because it allows features that otherwise were not be visible to the naked eye or in the polarised light mode, to be clearly seen in the fluorescent light mode. This is vital in explaining aspects such as the mechanisms underlying the development of channels around the fibres and the release of vapour pressure formed by evaporation of the water vapour during the early period of heating. These aspects are the main positive effects that are ascribed to the application of pp-fibres for reducing the risk of explosive spalling [Hannant 1998, Tatnall 2002, Segre et al. 1998].

3.3 Development of microcracks

The study further shows clear evidence of intense microcracking of the cement paste matrix and most of the coarse aggregate particles directly below the spalled surface and in deeper parts, down to about 55 mm, from the spalled surface. A large part of these cracks is obviously the result of heating, but a portion may be ascribed to the explosion that is associated with the spalling [Larbi and Nijland 2001, Larbi and Siemes 2000]. The latter is revealed by the sub-parallel to parallel pattern of cracking in the zone immediately under the surface of spalling, which is obviously caused by scaling of pieces of material from the surface as a result of the explosive spalling.

3.4 Decomposition and weakening of cement paste matrix

The results also show that the cement paste matrix, 5-10 mm directly below the spalled surface, had lost almost all of its original characteristics compared to the reference unheated samples. There was absence of ettringite ($CaO.Al_2O_3.3CaSO_4.32H_2O$), calcium hydroxide ($Ca(OH)_2$) and calcium carbonate ($CaCO_3$) in this zone. Also, the C-S-H had almost completely been decomposed and transformed into a less-cohesive material. All of these effects suggest that the temperature in this zone had exceeded or at least reached 950°C, the decomposing temperature of C-S-H. Moreover, the capillary porosity had increased considerably and the bonding of the cement paste matrix to most of the coarse aggregate as well as the cohesiveness of the concrete in the zone 45-55 mm directly below the spalled surface of the fire tested samples A and B was lost. All these effects, which under normal circumstances could not be explained because they are not visible to the naked eye, are made visible using the integrated microscopic method. The method also allows the assessment of the effectiveness of the pp-fibres to reduce damage due to explosive spalling.

3.5 Determination of the depth of attack

The depth of attack, that is, the total length of the region of the tested concrete element that is considered unsound and may have to be removed, was determined from the original surface of the tested elements up to the zone of reasonably 'sound' concrete, using the schematic diagram in Figure 9. In this analysis, the nominal length of each cylinder was assumed to be circa 450 mm, the original thickness of the concrete elements. For the two fire tested samples, the depth of attack, taking the amount of spalling into consideration, was found to vary between 55 mm for element A, containing 1 $kg.m^{-2}$ pp-fibres and 40 mm for element B, containing 3 $kg.m^{-2}$ pp-fibres. This total thickness or material loss of 9-12 % is considered quite small compared to the nominal thickness of the tunnel elements investigated.

3.6 RCM test

The results of the accelerated chloride migration test revealed that the presence of pp-fibres up to 3 kg of fibres per m^3 of concrete has no effect on the chloride ion penetration resistance. This effect has been confirmed up to ages of one year.

Another important observation was that the RCM values of the mixes decrease with increasing age. This is normal and was found for all types of concrete (with or without pp-fibres), with a stronger decrease for blast furnace slag cement and in particular with the tested binder containing fly ash, as compared to plain Portland cement concrete. All the four mixes show a time dependency that is very similar to an otherwise comparable mix without fibres.

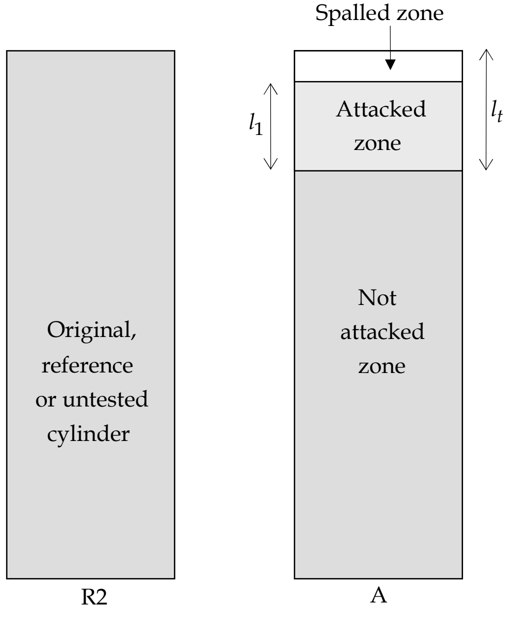


Figure 9: Schematic diagram, not drawn to scale, showing the method by which the depth of attack was determined from the tested tunnel elements. **R2** = *reference, dummy or untested cylinder,* **A** = *one of the tested elements showing the various zones that were used in the analysis.*

4 Concluding remarks

From the present study, the following conclusions can be drawn:

- Application of the pp-fibres could not avoid spalling: in the fire tested elements A and B, containing 1 kg.m^{-2} and 3 kg.m^{-2} pp-fibres respectively, spalling did occur. The fibres in both elements after intense heating by fire were found to have melted and subsequently evaporated, leaving channels in the cement paste matrix in the zone directly below the spalled surface up to a depth of about 55 mm in element A and 40 mm in element B. The channels formed are likely to have enhanced the release of vapour pressure built-up in the elements, which subsequently reduced explosive spalling. At least tentatively, the results show that with an increase of the fibre dosage, the extent of damage reduces.

- The cement paste matrix, 5-10 mm directly below the spalled surface, had lost almost all of its original characteristics compared to the reference unheated samples. Typical hydration products, such as ettringite, calcium hydroxide and C-S-H in this zone had been decomposed or transformed into less-cohesive phases.
- The depth of attack, determined from the original surface of the tested elements down to the zone considered to be reasonably sound, was found to vary between 55 mm for element A and 40 mm for element B. This material loss of 9-12 % is small compared to the nominal thickness of the tested tunnel lining elements.
- The use of an integrated microscopic analytical method, consisting of a combination of stereomicroscopy and polarising and fluorescent microscopy (PFM), makes it possible to assess the effectiveness of the use of pp-fibres in reducing the risk of explosive spalling in concrete exposed to fire. The method can be used to assess the distribution of the fibres in concrete and the effect of the fire on the concrete as well as on the fibres, which under normal circumstances could not be explained because they are not visible to the naked eye.
- Systematic investigation of the resistance against chloride ion penetration has shown that the absence or presence of polypropylene fibres up to 3 kg of fibres per m^3 of concrete has no considerable effect. Thus the durability of concrete with pp-fibres under aggressive load (de-icing salts, seawater) is not compromised. This has been confirmed up to ages of one year. The scatter in the results as well as their time dependency are similar to normal concrete (without pp-fibres) tested by the same method.

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