Factors to consider in using PP fibres in concrete to provide explosive spalling resistance in the event of a fire

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ABSTRACT: The use of polypropylene fibres in concrete to inhibit explosive spalling in the event of a fire is now becoming common practice in many parts of the world, particularly in tunnel construction. The number of projects using this technology is growing and with this has come an increased understanding of the sometimes conflicting technical and practical issues of using fibres to provide explosive spalling resistance. This paper reviews the many factors that must be considered in designing a fibre reinforced concrete, both cast in place and shotcrete, that meets not only the client's requirements for a cost effective construction exhibiting quality, performance and durability, but also the engineer's requirements for assured optimised resistance to explosive spalling. There are also the practical requirements, so important to the contractor, of being able to mix and place the concrete easily, on time and within the specification. Factors reviewed include fibre types, dosage, performance and safety margins, mixing and distribution, and effect on concrete properties.

1 INTRODUCTION

Concrete has been the primary material for construction for many years and the effect of fire on concrete has long been studied. This has been particularly the case in tunnels, where the impact both on human life and the structural integrity of the construction has always been a major factor in the designer's mind. However, after the Great Belt Tunnel fire in Denmark (1994), the Channel Tunnel fire (1996) (Figure 1) and the Kaprun Tunnel fire in Austria (2000) designers became even more focused on the structural fire protection of concrete tunnel linings. Apart from the tragic loss of human life, the damage sustained to tunnel structures can cause major disruption and enormous financial loss through the suspension of tunnel use and high repair costs. Reports suggest that the financial cost from direct damage and lost revenue of the Channel Tunnel fire was in itself in the order of £200m.

Investigations into the first Channel Tunnel fire in 1996 (Kirkland, 2002) and the second fire in 2008 (Flynn, 2008) reported that a significant loss of cross sectional area in the tunnel lining had occurred due to severe spalling of the high strength concrete that had been exposed to very high temperatures. Indeed, in some sections, the loss of concrete was so great that the embedded reinforcement steel had become so exposed that the structural integrity of the tunnel had been placed at risk.

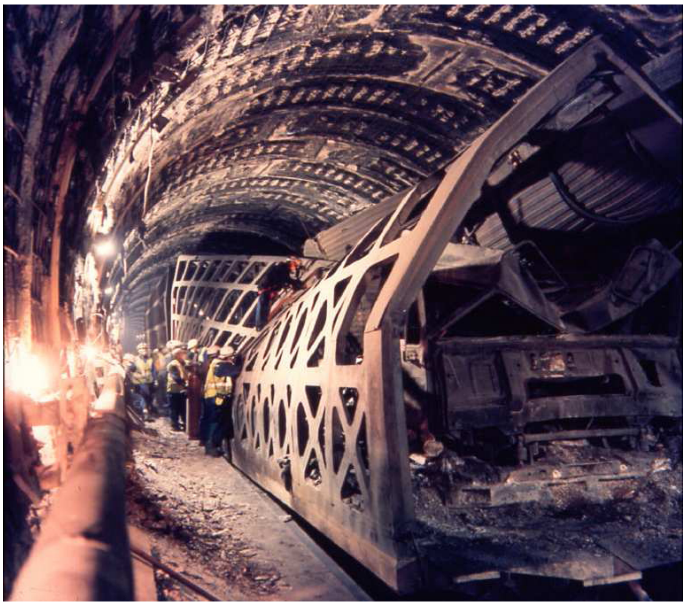

Figure 1. Channel Tunnel fire damage

This significant damage confirmed that while the strength and durability of high strength concrete is greatly superior to that of conventional concrete mixes (offering improved mechanical properties, low permeability and chemical resistance), it is far more susceptible to fire damage than normal concrete due to its high density and its intolerance to high pore pressures and internal tensile stresses when exposed to high temperatures. The extent of this damage raised significant concerns over the survivability and structural integrity of tunnel linings following a potential fire and prompted a great deal of international research (Kodur, 2000; Leipzig, 2009) into the factors involved in the spalling of concrete in fires and a search for cost effective solutions.

In the planning for the extension of the high speed rail line from the Channel Tunnel into London, known as the Channel Tunnel Rail Link (CTRL), the designers, following on from experience in refractory products and oil platform protection, commissioned detailed research into concrete containing polypropylene (PP) micro-fibres. Fire testing in small panels (Figure 2) through to full scale tunnel segments clearly demonstrated that the inclusion of appropriate PP monofilament micro-fibres provided the concrete with excellent intrinsic resistance to explosive spalling (Shuttleworth, 2001). The CTRL project subsequently became the first major tunnel project in the world to incorporate PP micro-fibres to provide explosive spalling resistance.

Figure 2. Test samples from CTRL testing - plain concrete & concrete with PP fibres.

However, not all PP micro-fibres have been found to prevent explosive spalling and with those that do, there can be significant differences in the degree of protection provided or their ability to be used in concrete without changing the mix design. Over the last decade a greater understanding of the detailed requirements needed to be designed into a suitable PP micro-fibre to optimize this technology has been gained. This paper reviews these issues and provides guidance on the specification of PP micro-fibres best suited to fulfil this very important function – the prevention of explosive spalling in concrete.

2 UNDERSTANDING CONCRETE SPALLING

Concrete spalling can be described as the breaking off of layers or pieces of concrete from the surface of a structural element when exposed to the high and rapidly increasing temperatures experienced in fires (Malhotra, 1984). Three different kinds of concrete spalling can be categorized, as described below.

2.1 *Surface spalling*

This affects aggregates on the concrete’s surface, whereby small pieces of concrete, up to 20 mm in size, are gradually and non-violently dislodged from the surface during the early part of the fire. This is usually caused by the fracture of pieces of aggregate due to physical or chemical change at high temperatures. In the case of surface spalling, the degradation of the concrete is relatively slow and involves the dehydration of the cement matrix followed by the loss of bond between aggregate and matrix. When the temperature rise of the concrete is relatively slow, the moisture in the concrete has time to migrate from the side exposed to the heat and pressure build up is minimal. The presence of moisture in this case can actually mitigate the effects of the temperature rise, since a great deal of energy is consumed in turning moisture to vapour.

2.2 *Corner break-off*

Corner break-off, which is also known as sloughing-off, occurs at the edges and corners of concrete elements during the latter stages of the fire when the concrete has cracked and weakened.

2.3 *Explosive spalling*

This is unquestionably the most serious and indeed most dangerous form of spalling that occurs during the first 20 – 30 minutes of a fire when the temperature in the concrete is in the range of 150- 250°C. Explosive spalling occurs when there is a rapid temperature rise, such as in hydrocarbon-fuelled fires following a traffic incident, where very large pieces of concrete can be violently ejected over several metres away from the concrete. As a fresh concrete face is presented to the fire, progressive explosive spalling deep into the concrete thickness occurs, threatening the structural integrity of the construction.

After several decades of research it is known that there is a complex combination of chemical, physical and thermodynamic factors involved that influence explosive spalling including moisture content, type and size of aggregate, concrete permeability, rate of heating, presence of reinforcement and external loadings. Experts agree that there is significantly more risk of explosive spalling when high strength, low permeability concrete is specified, because of the greater pore pressures that build up during heating.

The theories as to how and why explosive spalling occurs are predominantly based upon moisture movement. As the temperature of the concrete increases, the moisture in the concrete changes to steam vapour. If it is unable to escape from the concrete mass, this vapour creates a dramatic increase in pressure inside the concrete. As this process continues, the vapour pressure increases to the point where it exceeds the tensile capacity of the concrete, causing pieces of concrete to be violently and explosively dislodged from the element. As well as this conventional 'moisture movement' theory, there is also a consensus that aggregate expansion caused by thermal stresses also has a direct influence on explosive spalling.

3 HOW PP FIBRES INHIBIT EXPLOSIVE SPALLING

It has now been well accepted for many years that the addition of suitable polypropylene monofilament micro-fibres (Figure 3) can counteract explosive spalling in cast concrete (Ali et al, 1996) and in shotcrete (Wetzig, 2002), but in order to design an optimized micro-fibre to prevent explosive spalling, it is necessary to have an understanding of the detailed mechanism by which these fibres function. Since the spalling is caused by pressure created by a restriction on the movement of moisture/steam, then somehow the presence of the fibres must relieve that pressure.

Figure 3. Monofilament polypropylene fibres (PP)

As the temperature in the micro-fibre reinforced concrete rises the PP softens and begins to melt due to a progressive change of phase which starts at approximately 150°C when the crystallinity begins to break down into an amorphous polymer. It peaks at 165°C (the commonly quoted melting point), and is complete at approximately 175°C. It is this melting that is believed to facilitate the reduction in the internal stresses present in the concrete that cause the explosive spalling and there are two main theories that are proposed as to how the micro-fibres do this.

3.1 *Mechanisms*

Khoury (2008), whilst recognizing the possibility of other mechanisms, advocates what he terms a PITS (Pressure Induced Tangential Space) theory in which the steam overrides the expansion of the PP as it melts, to squeeze between the micro-fibre and the concrete matrix and pass along the length of the fibre. He claims that the effectiveness of such a mechanism would be dependent upon the cumulative surface area of the micro-fibre and connectivity of the fibres, and is therefore favoured by an ultrafine fibre with a diameter of around 18μm diameter that provides a very high number of fibres. Since micro-fibres are dispersed throughout the concrete as individual entities it is not clear how the connectivity of the fibres is created and how the steam pressure is alleviated. This theory also cannot explain why 32μm diameter micro-fibres, that provide only one third the number of fibres compared to 18μm diameter, have been proven to provide comparable and possibly slightly superior explosive spalling resistance (Jansson et al, 2008).

3.2 *Microcracking mechanism*

An alternative theory was presented by Sullivan (2001) who contends that as an individual PP fibre melts, its much higher coefficient of thermal expansion compared to that of concrete (8.5×) creates a large number of microcracks. These newly created microcracks can then link with the microcracks created by the thermal expansion of neighbouring micro-fibres, or from thermally induced stresses, to form an interconnecting network that can facilitate the movement of steam through the concrete. It is this permeability, which most importantly is created only should a fire event occur, that relieves the stresses created by the steam generation and counteracts the possibility of explosive spalling.

Liu et al (2008) found from backscattering electron microscopy (BSE) and gas permeability testing that the melting of the PP fibres increased the connectivity of the isolated pores leading to an increase in permeability, with peak permeability occurring at approximately 200°C (i.e. soon after the melting point of the polypropylene). It was concluded that the creation of microcracks and their connectivity into a network (Figure 4) were major factors in determining the permeability of the concrete upon exposure to high temperatures.

Saka et al (2009) report from preliminary numerical simulation studies that a single PP fibre embedded in a mortar matrix subjected to a temperature increase of 140°C creates a significant stress on the matrix because of the difference in the coefficients of thermal expansion. Khoury (2008) also indicates a significant tensile stress is exerted on the surrounding matrix by the large difference in thermal expansion between concrete and PP polymer leading to the creation of microcracks.

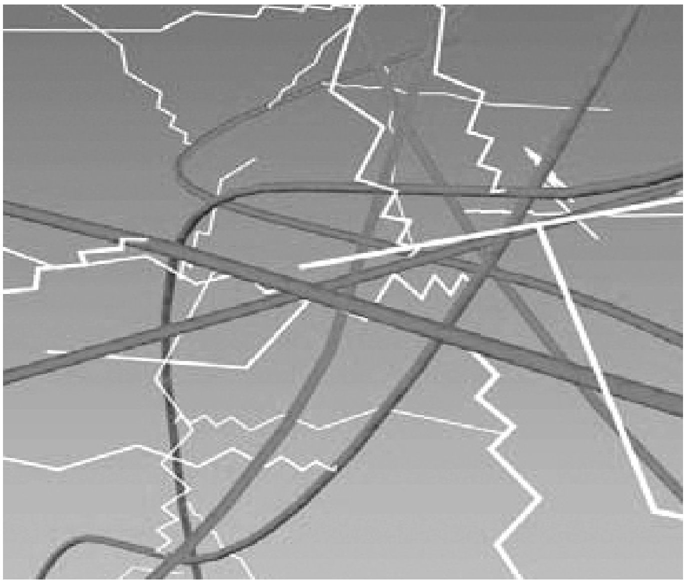

Figure 4. Microcracking network

Microcracks are also created in concrete by thermal effects such as aggregate expansion, drying shrinkage and steam generation. However, it is the supplementary creation of microcracks provided by the melting of the PP micro-fibres that operates in a serial/parallel system with these pores and interfacial transition zones (Kalifa et al, 2001) that provides the superior level of protection of the concrete against explosive spalling.

The larger the mass of the individual fibre, the higher will be the stress that the molten polymer can create and the increased tendency for microcracks to be formed as a result of this stress. However, too large an individual fibre leads to a lower number of fibres distributed throughout the concrete which reduces the network formation possibilities. Equally, at the other extreme, too small an individual fibre reduces the tendency for microcracks to be formed, restricting the network that can be created which reduces the overall ability of the fibre to prevent explosive spalling (Bostrom & Jansson, 2007). The optimum size of the fibre for the most efficient explosive spalling resistance lies between these two extremes.

3.3 *Optimum fibre dimensions*

Work done by Jansson & Boström (2008) compared the performance of 12 mm long PP micro-fibres of two different diameters (32µm and 18µm) in test panels made with concrete typically used in the construction of tunnels in Sweden. The tests were conducted under conditions designed to encourage an explosive spalling tendency, such as: using the more severe Rijkswaterstatt (RWS) fire curve of 2 hours with a peak temperature of 1350°C versus the standard Eurocode 1 fire curve of 1100°C for 2 hours (Efnarc, 2006) using large panels measuring 1200 × 1700 × 300 mm instead of small panels measuring 500 × 600 × 300 mm, using large aggregate versus smaller aggregate, and testing panels with high moisture content under compressive load and with low fibre dosages. They reported the spalling data shown in Figure 5.

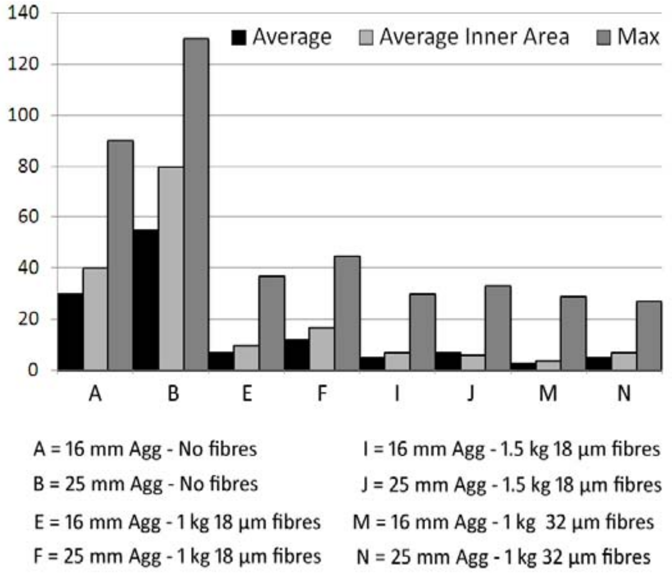

Figure 5. The spalling depths (mm) of large scale slabs after 30 minute fire exposure to RWS fire curve.

The data shown in Figure 5 obviously invalidates the theory that it is simply the number of fibres in the concrete that determines the effectiveness of a fibre to provide explosive spalling resistance. This is because the 32µm diameter PP fibres are seen to provide at least comparable performance to 18µm diameter fibres that are 3.2 times more numerous in the concrete. The data also indicates that panels containing 1.0 kg/m^3 of 32µm diameter fibre gave marginally better results than those containing the higher 1.5 kg/m^3 dosage of 18µm diameter fibre. The number of fibres in the concrete is a factor in performance but it is clearly not the dominant factor.

The above referenced research together with in-house research at Propex Concrete Systems in cast concrete and shotcrete (Tatnall, 2002) leads us to support the view put forward by Sullivan and others that it is the expansion of the molten PP fibre, which induces the microcracks to create a network for the pressure relief of the steam, that is the dominant mechanism in providing the explosive spalling resistance in concrete. The essential pre-requisite is that the microcracks must be created before the pressure relieving benefits of any network can be utilised. That mechanism is favoured by using a 32µm diameter fibre rather than a smaller diameter fibre, such as an 18µm diameter fibre.

In the same way, a fibre of 12 mm length will increase the individual fibre volume and promote the creation of microcracks in a fire more than a 6 mm long fibre, whilst still providing sufficient numbers of fibres (approx 120 million/kg) to create the required network for the dissipation of steam vapour. Although a 6 mm fibre can perform to a high level, a 12 mm fibre will be more effective, particularly under more severe conditions when the highest level of performance is required and where differences will be seen between fibres. Besides using a fibre of 32µm diameter and 12 mm length that favours explosive spalling resistance, there are several other very important requirements for fibres being incorporated into concrete that must also be addressed in order to arrive at a practical, viable fibre for the prevention of explosive spalling.

4 GENERAL REQUIREMENTS

With respect to the use of fibres, the different parties involved in a project can have differing requirements. The client wants a fire resistant, durable structure, fast construction, minimum maintenance in service, minimum loss of service during repair, reduced insurance premiums, and a cost effective solution. The designer/engineer wants certified explosive spalling resistance capability, quality assured materials, no negative impact on other concrete properties, ease of use in construction, and a cost effective solution. The contractor/concrete supplier wants a cost effective solution, ease of addition to concrete, and no concerns relating to mixing and distribution in concrete. It is obvious that the best overall specification will be a fibre that provides the optimum balance between proven explosive spalling resistance, practicality (trouble free usage) and cost effectiveness – a fibre that satisfies all of the interested parties requirements.

PP micro-fibres are compatible with steel fibres and chemical admixtures and have been found to mix, distribute, pump and be cast/wet sprayed in a similar way to unreinforced concrete/shotcrete. It has been found that the fine nature of PP fibres is not compatible with the dry shotcrete system (Wetzig, 2002).

5 TECHNICAL CONSIDERATIONS

5.1 *Fibre quality*

To provide confidence that the micro-fibres will consistently provide the full range of benefits, all fibres used for explosive spalling resistance should be PP monofilament micro-fibres (100 percent virgin polypropylene fibres containing no reprocessed olefin materials) conforming to EN 14889-2:2006 Class 1a and specifically engineered & manufactured in an ISO 9001 certified facility for use as concrete secondary reinforcement. Where applicable, fibres should also carry the CE marking. Fibrillated PP fibres provide a limited degree of protection whilst macro-synthetic and steel fibres have been found to have little or no influence on the prevention of explosive spalling.

5.2 *Fibre dosage*

Many researchers have demonstrated that the degree of spalling is influenced not only by fibre type but also by the fibre dosage (eg. Zeiml et al 2006, Bilodeau et al 2004). The concrete specification and the fire risk assessment are important factors to consider when selecting the dosage of PP micro-fibres to use for passive fire protection. Road tunnels generally present greater fire risks than rail tunnels owing to the unpredictability of the vehicles and the nature of goods transported within.

Accurate determination of the actual minimum fibre dosage that will provide the required explosive spalling resistance can, in reality, only be established by large scale fire testing of the actual concrete which is to be used on a specific project. This is a costly exercise and an expense many projects would like to avoid. Section 6.1 of the European Standard EN 1992 Eurocode 2 makes reference to the use of 2 kg/m^3 of monofilament polypropylene micro-fibres to control explosive spalling in high strength concrete. Many engineers follow this recommendation to eliminate the need for expensive testing in the knowledge that this dosage will provide a very good safety margin. This does not preclude the usage of lower dosages but it does highlight the need for careful consideration and a necessity to carry out fire testing on large concrete samples that completely replicate the materials to be used on an actual project. Where this has been done, dosage rates of, for example, 1.0 kg/m^3 and 1.5 kg/m^3 have been used in actual tunnel projects.

Whilst small scale sample testing gives indicative performance data that may be useful in making an initial selection of materials, it does not replicate the situation in a real tunnel fire and cannot provide the quality or range of data provided by large scale sample testing (Figure 6). Engineers should also be clear on what they consider to be the acceptable performance for spalling resistance. Some project specifications have stated that during fire testing there will be no explosive spalling permitted. Whilst this is entirely possible in small scale samples and with favourable mix designs, this would be almost impossible to achieve in large scale fire tests conducted on high strength concrete and adopting the most onerous RWS fire curve. What is most important is that the concrete does not experience “progressive spalling” which ultimately puts the entire structure at risk.

Figure 6. Large panel fire testing

If conventional rebar or fabric is to be used in the concrete structure then this should also be included in test samples, as the presence of steel reinforcement will have an influence on the degree of spalling experienced in a fire scenario. It should be noted that the use of PP micro-fibres does not reduce temperature development through the concrete, so careful consideration should be given to the depth of cover requirement over the steel reinforcement.

6 PRACTICAL CONSIDERATIONS

There have been several cases of projects where fibres have been selected purely on spalling results from small scale laboratory testing and then, when full scale site production has begun, the engineers and contractors have seen that some fibre products have a dramatically negative influence on the concrete, notably the workability, air content and compressive strength. Changes have then been made to the mix design in order to offset these negative effects and the fire testing data has been effectively rendered null and void. Therefore, during the selection process for PP micro-fibres it is imperative that designers take into consideration the effect of the fibres on concrete workability, air content, and strength.

6.1 *Effect on workability*

The efficacy of all fibre reinforcement is dependent upon achievement of a uniform distribution of the fibres in the concrete, their interaction with the cement matrix, and the ability of the concrete to be successfully cast or sprayed. Essentially, each individual fibre needs to be coated with cement paste to provide any benefit in the concrete. Regular users of fibre reinforcement concrete will fully appreciate that adding more fibres into the concrete, particularly of a very small diameter, results in a greater negative effect on workability and the necessity for mix design changes. This is because very small diameter fibres have a much higher combined surface area (eg. 18µm diameter fibres have a 77% higher surface area than 32µm diameter fibres). This extra demand on the cement paste, unless adjusted for by the addition of more water and cement or admixtures (thereby increasing costs), will ultimately have a dramatic effect on the workability of the concrete, particularly when dosages are above 1 kg/m³. Kompen (2008) has reported the experience in Norway that ultrafine fibres in wet shotcrete had an adverse effect on the water demand of the mix and that the fibres were released from the shotcrete and blocked air filters on the spraying machines.

6.2 *Effect on air content*

Another practical aspect to consider in the selection of PP micro-fibres is that bundles of very small diameter fibres are more difficult to distribute throughout the concrete and are known to entrain more air in the concrete. Comparative site studies have identified that the increased air content for concrete containing 18µm diameter fibres was around 5 - 8% compared to approx 1.0% for a 32µm diameter fibre. This increase has a negative effect on concrete strength which is not desirable in underground constructions. Some projects that have used 18µm diameter fibres have even resorted to using de-foaming agents to reduce air content. This will inevitably influence the in-place costs of the concrete and place a question mark over the validity of any fire tests carried out to assess the explosive spalling performance of the original concrete/fibre combination.

With a ~6% reduction in compressive strength for every 1% increase in air content, the use of ultrafine micro-fibres can result in a very significant loss of concrete strength. In an effort to divert attention away from the negative effects these very fine diameter fibres have on workability and air content, lower dosages have been suggested as the solution. Whilst this may be perceived as an interesting commercial proposition for contractors and ready-mixed concrete suppliers whose priority is to have a low cost solution, this suggestion reduces the degree of explosive spalling resistance and should not be accepted on the basis of small panel laboratory testing of concrete having an elevated air content. This increase in air content may not be a problem for shotcrete as the air is blown out during spraying, but if the performance of a fibre for a shotcrete mix is assessed on a panel made with cast concrete, the elevated air content can mask the true ability of the fibre to counteract explosive spalling when it is used in the actual shotcrete because the entrained air improves the possibility of a concrete panel passing a fire test.

6.3 *Addition & mixing of PP fibres*

The addition of PP monofilament micro-fibres to concrete is a relatively simple process depending on the size of the project. Fibres designed specifically for concrete reinforcement are normally supplied in fully degradable paper packaging that enables the desired dosage per unit volume to be simply added directly into the concrete truck or pan mixer. The packaging is designed to rapidly break down allowing uniform distribution of the fibres into the concrete. In relatively small projects this is often the most cost effective method to adopt, with packaging available in 1 kg or 2 kg bags.

Where projects involve significant quantities of PP micro-fibres, the contractors and ready-mixed suppliers often consider the use of more sophisticated, automated methods of adding fibres to the concrete. Fibre dosing machines ensure that the required amount of fibres is accurately measured and delivered automatically to the concrete mixer. There is a risk when using very fine fibres that because of the extremely high number of fibres being added to the concrete that they may stick together in bundles, becoming encased in cement paste and not evenly distributed throughout the concrete. This has been seen during fibre wash out tests when clumps of fibres have been observed. Obviously this is unacceptable because the protection against explosive spalling is not uniformly distributed in the concrete. This has not been an issue with the 32µm diameter fibres which have also been found to work very well in the automated fibre dispensing and delivery systems.

6.4 *Improvements in shotcrete*

The benefits of using suitable PP micro-fibres in shotcrete are not only restricted to enhancing resistance to spalling during fires. PP micro-fibres have been added to wet shotcrete for many years to provide several operational and performance benefits including: the ability to apply greater thicknesses in a single pass, reduced rebound and sloughing, enhanced impact and abrasion properties, early-age crack control, reduced line pressure in spray pumps, reduced dosage of accelerator and increased resistance to freeze-thaw cycling.

7 COST EFFECTIVENESS

The introduction of PP micro-fibres is now widely recognized for providing passive fire protection to both shotcrete (Larsson, 2006) and cast concrete (Court, 2003) structures and an extremely cost effective solution when compared to alternatives such as sprayed coatings or barrier methods. Savings in materials, labour and project time have all been seen in practice. Many major tunneling projects now incorporate this technology to provide insurance against explosive spalling in the event of fire, including for example the Gotthard Base Tunnel (Switzerland), the Brenner Eisenbahn Tunnels (Austria), the Channel Tunnel Rail Link (United Kingdom) (Court, 2003), the Weehawken Tunnel (USA) (Ozdemir, 2006), the Epping-Chatswood Rail Line (Sydney, Australia) (Schmidt, 2005), EastLink Tunnels (Melbourne, Australia) (Highway Engineering, 2007) and the Lane Cove Tunnel (Sydney, Australia). Many clients follow the recommendations of European Standard EN 1992 Eurocode 2 and specify 2 kg/m^3 dosage because it provides proven performance with a good safety margin. Depending upon tunnel usage and risk assessment it may be possible to reduce the dosage to a lower level but this may require a programme of large scale fire testing to provide evidence that this dosage is indeed acceptable in a specified mix design. The additional cost for carrying out such testing may well prove unattractive to many projects.

During the selection process, designers and contractors should not simply look at the basic cost of fibres, they should carefully compare “in-place” concrete costs. This will ensure that the positive and negative effects of all fibres, together with any additional cement or admixture costs, are taken into account. Because concrete incorporating 32µm diameter fibres does not suffer from as many negative side effects as observed when using 18µm diameter fibres, the former type of PP micro-fibre provides a more cost-effective option.

8 CONCLUSION

If fibres are to be used to provide explosive spalling resistance in shotcrete or cast in place concrete they should satisfy two main criteria in order to meet all of the requirements of the interested parties. These include a demonstrated ability to counteract explosive spalling together with producing no negative side effects in the concrete. These criteria have been found to be best achieved by using a fibre made of polypropylene monofilament of 32µm diameter and 12mm length manufactured to, and complying with, ISO 9001 & EN14889-2 standards.

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