ADFIL Construction Fibres

TECH NOTE

Fibres for use in concrete for fire resistance

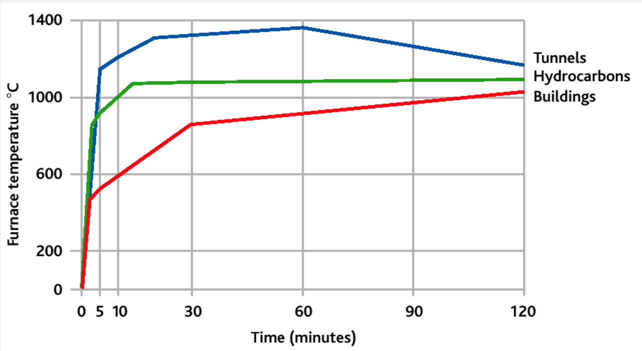
Ignis®

For the last 16 years ADFIL has been promoting the use of its Ignis fibres to reduce explosive spalling in concrete. Whilst initially supplying relatively small quantities, mainly for refractory products, this changed exponentially after the Channel tunnel fire in 1996. Other tunnel fires (see Table A) have also helped to focus engineers' and specifiers' minds on finding a relatively low-cost solution to reducing the loss of life and the economic cost associated with the closure of these key transport routes.

Whilst a significant amount of research has been conducted on mainly a project by project basis, there is one common conclusion and that is the use of polypropylene fibres in concrete subjected to fire, significantly reduces the risk of explosive spalling. The following information is aimed to briefly summarise the types of fire curves used, the mechanism of spalling and the theory behind why the fibres work.

Types of fire curves

Several fire curves are commonly used across Europe. The curve used usually relates to the potential fire load that could realistically be attributed to that tunnel. As seen in graph A the fire curves vary significantly from the ISO 834 curve up to the Riijkswaterstaat (RWS). The severity of the test often relates to not only fire load, but other factors such as:



Graph A: Standard fire curves for three scenarios: tunnels, hydrocarbons and buildings

1. Location of the tunnel, is it under a river or the sea?
2. Does the tunnel run through stable or unstable rock?
3. If the tunnel collapses will it make escape bays or chambers inaccessible?
4. Economic impact of total collapse of the tunnel.
5. Design life of the tunnel.

Spalling mechanism

There are three main mechanisms which cause explosive spalling to occur in concrete subjected to fire: Water vapour formation, chemical and thermal processes.

Water vapour formation

The transition of water from a liquid to a gas under identical pressure conditions means that the vapour occupies a volume approximately 1100 times greater than for the same mass of water. Since this volume change may not be always accommodated within the concrete, pressure builds up until the tensile strength of the concrete is surpassed, leading to an abrupt release of pressure, causing the breakaway of concrete fragments in an explosive manner away from the main body of the concrete.

Chemical processes

During a fire, the raw materials from which the concrete is made, begin to alter chemically. For instance at 200 °C some flint aggregates start to dehydrate, at 300 °C the siliceous materials contained in the concrete exhibit a loss in strength. At 400°C dehydration of the calcium hydroxide present in the

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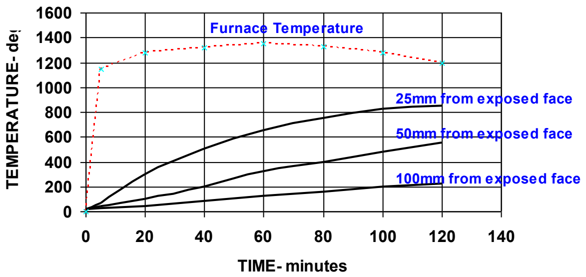
cement paste starts to occur and this decomposition starts to cause the strength of the concrete to deteriorate. For concrete containing Quartz, at 575 °C the mineral starts to expand and as a consequence of this increase in volume, the concrete structure will exhibit signs of bursting.
At about 800 °C concrete containing limestone will start to deteriorate rapidly as decarbonisation of the limestone will lead to the CO_2 exiting the concrete as a gas. If its route is blocked it can cause further damage to the structure.



Graph B: Typical temperature profile within concrete during test

Thermal processes

Due to the high temperatures present in such fires, the concrete will experience changes in length. Therefore, expansion needs to be considered as a design parameter. In addition to the changes in length, the concrete can experience "onion skin" peeling, which is caused by internal stresses within the concrete due to the different temperatures between the surface exposed to the heat and the cooler zones within the concrete.

As a consequence of the above mechanisms, the placement of any structural steel in the concrete has to be carefully positioned so as not to become exposed to high temperatures. At 700 °C the load carrying capacity of the steel is reduced to approximately 20 % of its value at normal temperatures.

How do the fibres help to reduce explosive spalling?

In order for the polypropylene fibres to work effectively, it is important to source the correct concrete ingredients in order to minimise the risks seen above.

Research into the reasons why the inclusion of polypropylene fibres work so effectively are moving apace, especially through academic studies lead by experts in many European countries.

In essence, the polypropylene fibres work by allowing moisture and water vapour to escape away as the temperature of the concrete exposed to a fire increases. As can be seen in graph B the temperature of the concrete heats gradually from the surface inwards.
In the first instance, due to a polarity mismatch there is poor adhesion between the concrete and the polypropylene fibres. This will allow the transfer of moisture under pressure through the channel between the concrete and the fibre.

In addition to this as the fibre starts to heat up during a fire, they will contract in length and expand in width. This is a reversal of the effect of the actual manufacturing process which actually stretches and orientates the fibres. This contraction will then create cavities in the concrete, which could lead to gas transfer within the concrete matrix. It has been theorised that this expansion of the polypropylene could cause micro cracks in the matrix which will also allow the movement of moisture away from the fire.

For fibre at the surface they would almost certainly be vaporized immediately creating a channel though which the moisture can escape. As the concrete continues to heat, the fibres contained in the concrete would gradually go through a cycle of melting then pyrolysis and finally combusting. This would then form a chain of interconnecting channels which therefore help to reduce explosive spalling caused by the expansion of water.

Which parameters influence explosive spalling?

Microfibre type

As explained earlier PP microfibres can avoid explosive spalling. The performance of microfibres is directly linked to the specific surface and hence the diameter of the fibres. This conclusion was first published by Khoury, G.A. and Willoughby, B. Polypropylene fibres in heated concrete Part 1 & 2 (2008). It presents a theory based on the Pressure Induced Tangential Space (PITS) which suggests that the steam escapes along the spaces between the PP fibres and the concrete even before the fibres melt. This means that the cumulative surface area of the fibres and their interconnectivity are critical factors. In the experimental report from 2010 Khoury, G.A. proves the above theory to be correct by performing fire test on 10 different sample unloaded in a hydrocarbon fire reinforced with a range of fibre (12, 15, 17 & 32μm). The conclusion of this report was:
There is a clear trend of decreasing explosive spalling with decreasing fibre diameter, where the fibres with nominal diameters of 12 & 15 microns experiencing no explosive spalling and the specimens without fibres at all experiencing the maximum explosive spalling. The fibres of intermediate diameters experienced explosive spalling in relation to their diameters. The trends supports the theoretical assessment.

Nature of the aggregate

influences the occurrence of fire spalling in several ways. The structure and the mineral composition are the most important factors influencing the thermal expansion of the aggregate according to Zoldners (1968). An important factor is the magnitude of quartz in the rock material. Quartzite and sandstone with high quartz content exhibit high thermal expansion in contrast to limestone without quartz which has a low thermal expansion coefficient. At 573 oC, quartz undergoes a sudden thermal expansion when a-quartz transforms to β-quartz. This expansion is non-reversible and can be used as an indicator of the magnitude of the temperature exposure in post fire investigations.

Water content

Moisture content plays an important role in the phenomenon leading to fire spalling. If the moisture content of the concrete is low, the probability of spalling is low as concluded by Meyer -Ottens (1972) and Copier (1979). Whether it is the absence of free moisture or the method of reducing moisture that limits spalling is a interesting question. A forced drying processes or long drying time changes the concrete so identical specimens with and without a high moisture content are hard to manufacture. A drying process, in an externally dry climate, induces micro cracks by shrinkage of the cement past. In contrast, when continuous hydration is dominant in reducing moisture, as in the case of concrete with low water/cement ratio, the pore structure changes.

Independent of the drying method, the process of drying changes the concrete sample fundamentally, i.e., it is not possible to have two identical specimens with different moisture contents. Despite the inherent uncertainty concerning why moisture content is important in spalling, moisture content does appear to be an indicator of the spalling risk. Under a certain moisture content some authors regards concrete as "safe" from explosive spalling. In Eurocode 2 (EN 1992-1-2:2004) a limiting value of 3 % moisture content by weight is recommended although the value can be changed in the national annex. Also Hertz (2003) and Bushev et al. (1970) point out the limit of 3 %.

Restraint to expansion

Restraint to expansion has also been identified as a key factor. Copier (1979) states that when a compressive stress is present, spalling is promoted, but the size of the compressive stress is less important. This conclusion was also drawn by Boström & Jansson (2007) when testing self compacting concrete, fire exposed from one side.

BRE sample without Ignis subjected to European Hydrocarbon Curve showing severe spalling

BRE sample with Ignis subjected to European Hydrocarbon Curve showing no spalling

Conclusion

The use of polypropylene fibres is now used in every continent for its ability to reduce explosive spalling in concrete; mainly in tunnels. It is now time for the engineering community to look seriously at using polypropylene fibres more widely in concrete structures above ground.

Year	Tunnel	Length (m)	Deaths
1978	Velsen, Netherlands	770	5
1979	Nihonzaka, Japan	2,045	7
1980	Kajiwara, Japan	740	1
1982	Caldecott, Oakland, USA	1,028	7
1983	Pecorile, Savone, Italy	600	8
1986	L'Arme, Nice, France	1,105	3
1987	Gumefens, Bern, Switzerland	340	2
1993	Serra a Ripoli, Italy	442	4
1994	Huguenot, South Africa	3,914	1
1995	Pfander, Austria	6,719	3
1996	Channel Tunnel, UK/ France	50,500	-
1996	Isola delle Femmine, Italy	148	5
1999	Mont Blanc, France/ Italy	11,600	39
1999	Tauern, Austria	6,400	12
2000	Kaprun, Austria	3,300	155
2001	Gotthard, Switzerland	16,942	11
2013	Gudvangatunnel, Norway	11,428	-

Table A: Tunnel fires

References

Bryan G Wiloughby, Polypropylene: Temperature –dependent structure and properties, January 2007

Gabriel Khoury, Newcon project, Tunnels and tunnelling, Spring 2006

Gabriel Khoury, Explosive spalling, Concrete, November 2006

Volker Wetzig, Fire protection in tunnels, Efnarc technical committee draft