THE USE OF PP FIBERS IN TUNNEL CONSTRUCTION TO AVOID EXPLOSIVE CONCRETE SPALLING IN CASE OF FIRE. NEW TEST RESULTS FOR THE CLARIFICATION OF THE MODE OF ACTION

Dr. Ingo Knack
Baumhueter extrusion GmbH, Rheda-Wiedenbrück, Germany

Abstract
In tunnel construction PP fibers are being increasingly mixed into the concrete to prevent explosive concrete spalling in case of fire, being caused by evaporation of the moisture contained in the concrete. In general opinion the increased fire resistance is based on the fact that by the melting fibers in case of fire capillaries are formed in the concrete through which the steam can escape. The exact mode of action of the PP fibers is not yet clear in detail and there are different model conceptions in discussion. In a previous work we have already demonstrated that in this connection the diffusion of the polymer melt into the concrete is the determining process.

In this work now test results with new PP and PE fibers are presented which were developed particularly for the further clarification of the mode of action. The test results clearly prove that the diffusion process of the melting PP fibers is the only mechanism which in case of fire leads to a permeable capillary system to reduce the harmful pore pressure in the concrete. There was no indication for any other processes.

1. INTRODUCTION

If concrete is heated up very quickly to high temperatures by extreme fire effect, as for example in the case of a hydrocarbon fuelled fire in a tunnel, the evaporation of the moisture contained in the concrete can lead to an explosive spalling of concrete fragments. This reduces the load bearing cross-section of the concrete and the exposed reinforcement very quickly loses strength in the heat. As the process continues, the structural element can completely fail. This kind of destructive concrete spalling can be avoided by the mixing of PP fibers into the concrete. The melting of the PP fibers in the case of fire leads to the formation of capillaries in the concrete for the relief of the steam pressure. Numerous experimental investigations, in particular large-scale fire experiments on tunnel segments (lining segments), have repeatedly confirmed this. Many tunnel projects have already been and are being carried out with the addition of PP fibers in order to meet specifications for fire resistance [1,2]. The Österreichische Vereinigung für Beton und Bautechnik (Austrian Concrete and Civil Engineering Association) in Vienna has adopted the addition of PP fibers for increasing fire resistance into the Fibre-Reinforced Concrete Guideline [3]. The German railways Deutsche Bahn AG also deals topically with this subject [19].
As a manufacturer of PP fibres the question has occupied us which mechanisms cause the
discharge of the steam pressure when the PP fibres melt in the case of fire and the
possibilities for optimisation of the fibres that can be derived from that.

The guiding idea in the subsequent development work was the consideration that the
diffusion of the polymer melting into the concrete matrix was the essential mechanism for the
fire protection effect of the PP fibres. The faster a permeable capillary system for the
dissipation of the steam pressure can be formed by the diffusion of the polymer melting, the
better the fire protection effect must be. Hence, the rate of diffusion of the polymer melting
becomes the determining influencing variable in this process. The rate of diffusion of a
material depends on its molecular size. Small molecules diffuse faster than larger ones.
Therefore the diffusion of the polymer melting into the concrete matrix must take place
faster, the smaller the PP molecules are. The smaller the PP molecules are, the lower the
viscosity of the polymer melting will be. The fluidity of the polymer melt, which is easy to
determine by measurement, is then the measure of its rate of diffusion and thus ultimately of
the fire protection effect of the fibres used.

Experimental results will now be presented in this work that confirm the correctness of this
deliberation in impressive fashion. These experiments have only now become possible, after
baumhueter extrusion GmbH found ways to manufacture polyolefin fibres with widely
varying melt viscosities. Hence, PP fibres are now available that form a very low viscosity
melt when heated. With PE fibres it is possible to go in the other direction; i.e. fibres are now
available here that form a very high viscosity melt or do not melt at all (rubber-like
consistency).
Due to these particular characteristics, the new PP and PE fibres now offer a unique
opportunity to check the diffusion model experimentally. For the fire experiments on which
we report here, fibres were selected that cover the entire range of flowability of the polymer
melt.

2. EXPLOSIVE CONCRETE SPALLING IN THE CASE OF EXTREME FIRE LOAD USE OF PP FIBRES

2.1 The spalling process
Fast heating and the development of high temperatures in concrete result in thermo-
mechanical stresses and an increased pore pressure due to the evaporation of water. If this
pressure cannot be relieved fast enough, the tensile strength of the concrete will ultimately be
exceeded and larger or smaller fragments of concrete will be blown off in an explosive
manner. The pore pressure is the crucial variable in this process and this has therefore been
examined in many experimental and theoretical works [6, 7, 8, 9]. The rapid increase in pore
pressure is facilitated by the following factors:

- high levels of moisture in the concrete (strong spalling only with moisture contents
  >3%)
- fast rise in temperature (fast evaporation of the water)
- high strength of the concrete (lower porosity, steam cannot escape as easily).

2.2 Use of PP fibres / current state of knowledge on the mode of action
In the case of fire, the harmful pore pressure in the concrete is reduced by the use of PP
fibres so that the feared explosive spalling of concrete fragments does not occur. This
representation of the process is generally accepted [7, 8, 10, 11, 12, 16]. On the other hand,
the microscopic processes in the periphery of the fibres, which are embedded in the concrete
and which melt in the case of fire, has not been fundamentally clarified in detail. Therefore different conceptions of the action mechanism are discussed.

The following mechanisms for the dissipation of the pore pressure by PP fibres are discussed and are evaluated differently in their significance:

a) Transport of water / steam along the boundary layer between the fibre and the concrete matrix
This model assumes that there is only minimal adhesion between the hydrophobic fibres and the cement matrix, so that the capillary transport of water or steam along this loosely structured boundary layer is possible and already sets in even before the fibres begin to melt. This mechanism is designated by G.A. Khoury as PITS (pressure induced tangential space) and is estimated to be very important [10, 11].

b) Formation of microcracks in the concrete in direct proximity to the embedded fibres
According to this model, microcracks are formed in the vicinity of the fibres due to stresses in the concrete caused by differences in the linear thermal expansion coefficients of the fibre polymer and the concrete, as well as the increase in volume when the fibres melt [11, 12, 13]. The microcracks ultimately form a connected network, via which the steam can escape. This is the dominant mechanism according to K. Smith and T. Atkinson [14, 15].

c) Thermal decomposition (pyrolysis) of the polymer mass
This process first starts at around 325 °C and is completed at around 475 °C [10, 11]. This is of no meaning for the explosive spalling, which begins very early at concrete temperatures of 150-250 °C [11] or 190-250 °C [16].

d) Formation of capillaries by the diffusion of the polymer melting into the concrete
Due to the melting of the PP fibres and the partial or complete absorption of the polymer melting by the surrounding concrete matrix, capillaries are formed at the location of the embedded fibres via which the steam can escape. This mechanism is favoured by Kalifa et al. [16], but positively excluded by Khoury [10, 11, 12] due to the high viscosity of the polymer melt.

2.3 The new PP fibre PB Eurofiber HPR with greatly increased flowability of the polymer melting and thus significantly improved fire protection effect
Concrete is a heterogeneous system that is more or less capillary depending upon its strength, and is therefore capable to absorb gases and liquids. This is shown among other things by the well-known problem of reinforcement corrosion due to carbonatation (absorption of CO2) and chloride (absorption of de-icing salt). The absorption of polymer melting by the concrete upon melting of the PP fibres should therefore be possible in principle. A low-molecular polymer structure and thus a low viscosity of the polymer melting facilitate this diffusion process. The faster the fine capillaries through which the steam can escape are formed by the diffusion of the polymer melt, the better the fire protection effect must be. That was the basic concept behind the further development, which in the end led to the new PP fibre PB Eurofiber HPR with a substantially improved fire protection effect.

The special characteristic of this new fibre, which has already been reported on in detail in an earlier article [4], is the enormously increased flowability of the polymer melting. The fibre has proven in numerous laboratory tests to be extremely effective in the prevention of explosive concrete spalling, despite the considerably lower dosage compared to a corresponding standard PP fibre. In the meantime the PB Eurofiber HPR fibre has also been
tested successfully in a large fire test. For this purpose a tunnel lining segment was manufactured with a dosage of only 900 g/m³ of this new fibre and tested at the MFPA in Leipzig under a temperature load in accordance with the EBA temperature curve and under an additional mechanical load. The tubbing was still completely intact afterwards; there was no discernible spalling [5]. Equally good results were achieved with standard PP fibres only from a dosage of 2 kg/m³ upwards.

The results obtained with this special fibre are the first confirmation that the diffusion capability of the polymer melt is the crucial influencing variable in the process of the fire protection effect of the PP fibres. In order to further support this model conception, the experiments were continued using newly developed fibres with different melt viscosities.

### 3 NEW EXPERIMENTS FOR CLARIFYING THE MODE OF ACTION OF POLYOLEFIN FIBRES IN FIRE PROTECTION CONCRETE

The experiments described in detail below pursued the goal of verifying the hypothesis that the opening of the fibre channels by the diffusion of the polymer melting into the concrete matrix is the crucial mechanism in the prevention of explosive concrete spalling by the PP fibres used. If this theory is correct, then the effectiveness of the fibre should be exclusively a function of the viscosity of the polymer melting. The PP and PE fibres with decreasing or increasing melt viscosities newly developed by baumhueter extrusion GmbH now offer a first-time opportunity to test this hypothesis experimentally, because PP fibres with a decreasing melt viscosity (increased rate of diffusion) ought to exhibit less and less spalling. Accordingly, cross-linked PE fibres with higher melt viscosities (reduced rate of diffusion) should exhibit more spalling.

#### 3.1 Test method / definition of the test conditions

The fire tests were performed on small test specimens (cubes with an edge length of 10 cm). The concrete test specimens were manufactured and the fire tests were performed in cooperation with the concrete test laboratory Reckenberger Betonprüfung- und Überwachungsgesellschaft m.b.H., Rheda-Wiedenbrück, Germany. The test conditions were the same as in the preceding investigations [4] and were consciously selected such that the strongest possible spalling behaviour was to be expected in order to make the differences more pronounced when using the various fibre types and variable dosages:

- high moisture content (approx. 5%) of the test specimens achieved by means of storage under water up until the anneal trial
- high strength (approx. 50-55 MPa) after 7 days
- extremely high temperature gradient by placing the test specimens in an annealing furnace heated to 1100 °C. The temperature gradient here is several orders of magnitude higher than in the case of the RWS or EBA fire curve with a temperature gradient of approx. 240K/min!

To evaluate the degree of spalling more accurately and objectively, a special evaluation method was developed that allows to determine precisely the volume of spalled fragments.

The test procedure is very reliable and its results show the well-known relationships:
clear relationship between spalling and the moisture content of the test specimens (no spalling at <3% moisture)
clear relationship between spalling and the strength of the concrete used, as figure 1 below shows:

Figure 1: Volume of the spalled fragments in relation to the concrete strength in the case of 0-concrete with no addition of fibres.

A concrete mixture based on the cement type CEM I 42.5 RHS was used to manufacture the cubes. Concrete mixtures were tested without fibres (0-concrete) and with the addition of PP fibres (dosages 500g/m³ and 750g/m³) and PE fibres (dosage 2 kg/m³).

Fresh concrete data:

- Water/cement ratio: 0,5
- Slump: 42-44 cm (corrected accordingly with superplasticiser in the case of fibre addition)
- Air void content: approx. 1,5%
- Fresh concrete green density: approx. 2.4 t/m³

The mixture was poured into steel moulds, compacted and de-aerated on a vibrating table and left in the mould for 1 day to harden. The cubes were subsequently stored under water for 7 days until the anneal trial.

Hardened concrete data before the anneal trial:

- Strength: approx. 50-55 MPa
- Moisture content: approx. 5%
For each anneal trial, two cubes were placed together for 5 minutes in an annealing furnace heated to 1100 °C. When spalling occurred (in particular in the case of the 0-concrete with no addition of fibres), this took place within the first 1-2 minutes and was clearly audible. Afterwards the cubes were removed from the furnace, visually assessed and photographed. After cooling, the remaining cube volume was determined, from which the volume of the spalled fragments was calculated. Four cubes were tested in each trial.

3.2 Concrete spalling in relation to the fluidity of the polymer melting of the fibres used

PP fibres with increasing fluidity of the polymer melting and PE fibres with decreasing fluidity of the polymer melting were used, including a special highly cross-linked and therefore infusible variant. The fluidity of the polymer melting of the different fibres was determined on the basis of the MFR value (Melt Flow Rate) in accordance with DIN EN ISO 1133. In this measuring method, the polymer melting is pressed through a standard nozzle at a specified temperature (e.g. 230 °C in the case of PP) with a specified weight (e.g. 2.16 kg). The mass in g thus obtained, calculated to the time unit 10 min, is designated the MFR value. High MFR values thus correspond to a high fluidity (low viscosity) of the polymer melting and low MFR values correspond to a low fluidity (high viscosity) of the polymer melting. The PP fibres normally used for fire protection in tunnel construction have MFR values within the range of approximately 20-30 g/10min. By comparison, the MFR value of the new HPR fibre is several orders of magnitude higher (MFR >1000 g/10min).

The following two chapter describe the results of the experiments in which the spalling behaviour was examined in relation to the fluidity of the polymer melting of the fibres used. The different variants of the PP and PE fibres mentioned above cover the entire range of the fluidity of the polymer melting, from non-flowing (fibre infusible) through slow-flowing to very fast-flowing. The goal of the tests was to prove that the fluidity and the associated diffusion capability of the polymer melting is the crucial factor in the fire protective effect of the PP fibres used.

3.2.1 Increasing fluidity of the polymer melting - test with variants of the PP fibre PB EUROFIBER HPR 2.8dtex(19.8μm)/6mm

The fibres used had MFR values of 600, 900, and 1800 g/10min. The dosage was 500g/m³ and 750g/m³ in each case. The results are shown in Table 1, Table 1.1 and Figure 2. The mean value from 4 individual measurements is given in each case.

Table 1: Spalling (cm³) with PB Eurofiber HPR 2.8dtex(19.8μm)/6mm in relation to the MFR value at the dosages 0.5 kg/m³ and 0.75 kg/m³.

<table>
<thead>
<tr>
<th>Fibre dosage</th>
<th>0-concrete</th>
<th>MFR 600</th>
<th>MFR 900</th>
<th>MFR 1800</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 kg/m³</td>
<td>37,7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,5 kg/m³</td>
<td>12,5</td>
<td>5,5</td>
<td>2,4</td>
<td></td>
</tr>
<tr>
<td>0,75 kg/m³</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Table 1.1: Spalling (%) with PB EUROFIBER HPR 2.8dtex(19.8μm)/6mm in relation to the MFR value at the dosages 0.5 kg/m³ and 0.75 kg/m³.

<table>
<thead>
<tr>
<th>Fibre dosage</th>
<th>Spalling volume in % compared to 0-concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-concrete</td>
</tr>
<tr>
<td>0 kg/m³</td>
<td>100</td>
</tr>
<tr>
<td>0.5 kg/m³</td>
<td>33.2</td>
</tr>
<tr>
<td>0.75 kg/m³</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2: Spalling (%) with PB EUROFIBER HPR 2.8dtex/6mm in relation to the MFR value at a dosage of 0.5kg/m³ compared to 0-concrete with no addition of fibres.

As the results at a dosage of 500 g/m³ show, spalling decreases continually as the MFR value increases, i.e. as the fluidity and diffusion capability of the polymer melting increase. No spalling was observed with the three HPR variants at a dosage of 750 g/m³.

3.2.2 Decreasing fluidity of the polymer melting - test with variants of the PE fibre PB EUROFIBER CUT F-2427 4dtex(23.3μm)/6mm

The setting of the different MFR values was carried out by varying the cross-linking of the PE fibre polymer. Since a poorer fire protection effect was to be expected with these fibres due to the significantly lower fluidity of the polymer melting compared to the special HPR fibre, the usual standard dosage of 2 kg/m³ was selected here. The following variants were tested:

- Original fibre, MFR 30, melting point approx. 95 °C
- Lightly cross-linked, MFR 11, melting point approx. 95 °C
- Moderately cross-linked, MFR 4, melting point approx. 95 °C
- Highly cross-linked, MFR 0, not fusible (rubber-like consistency)
The results are shown in Table 2, Table 2.1 and Figure 3.

Table 2: Spalling (cm³) with the PE fibre PB Eurofiber CUT F-2427 4dtex(23,3μm)/6mm in relation to the MFR value at a dosage of 2 kg/m³.

<table>
<thead>
<tr>
<th>Fibre dosage</th>
<th>0-concrete</th>
<th>MFR 30</th>
<th>MFR 11</th>
<th>MFR 4</th>
<th>MFR 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 kg/m³</td>
<td>23,4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 kg/m³</td>
<td>6,4</td>
<td>17,7</td>
<td>27,4</td>
<td>48,2</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Spalling (%) with the PE fibre PB EUROFIBER CUT F-2427 4dtex/6mm in relation to the MFR value at a dosage of 2 kg/m³.

<table>
<thead>
<tr>
<th>Fibre dosage</th>
<th>0-concrete</th>
<th>MFR 30</th>
<th>MFR 11</th>
<th>MFR 4</th>
<th>MFR 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 kg/m³</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 kg/m³</td>
<td>27,4</td>
<td>75,6</td>
<td>117,1</td>
<td>206</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Spalling (%) with the PE fibre PB EUROFIBER CUT F-2427 4dtex/6mm in relation to the MFR value at a dosage of 2 kg/m³ compared to 0-concrete with no addition of fibres.

As the result clearly shows, spalling increases as the fluidity and diffusion capability of the polymer melting decrease. In the case of the highly cross-linked, infusible PE fibre, the result is even significantly worse than with the 0-concrete with no addition of fibres. Diffusion of the polymer melting and thus the opening of capillaries through which the steam can escape are no longer possible with this fibre. In addition to the increased pore pressure, the thermal...
expansion of the rubber-like polymer mass leads to thermo-mechanical stresses in the concrete and, finally, to strongly increased spalling.

4. SUMMARY AND DISCUSSION OF THE RESULTS

The results of the tests described here confirm the correctness of the diffusion model without exception. There is a strong correlation between the viscosity of the polymer melting of the fibres used and the amount of concrete spalling. The results thus clearly prove that, when PP fibres are used, the diffusion of the polymer melting into the concrete matrix in the case of fire is the mechanism that leads to the opening of capillaries in the concrete through which the steam pressure can be rapidly relieved.

The molecular size decreases in the PP fibre variants as the MFR increases. Accordingly, diffusion is improved, the capillaries are opened faster, and spalling decreases.

In the PE fibre variants with decreasing MFR values, the molecular size increases due to cross-linking. Diffusion is hindered or is only partially possible and the capillaries are opened more slowly. Spalling increases accordingly.

The lower melting point of the PE fibres compared to PP is of no importance. This result, which we had already determined in our earlier experiments [4], is a further confirmation of the diffusion model, because there is no connection between the melting point of a polymer and the fluidity and diffusion capability of the polymer melt. The non-cross-linked PE fibre that melts at 95 °C forms a similarly viscous melt as the standard PP fibre that melts at 165 °C.

A speciality among the fibres used here is the highly cross-linked PE fibre, which no longer melts when heated, but forms a soft elastic mass. This characteristic makes the fibre particularly interesting and unique for fire tests to study the mode of action of thermoplastic polyolefin fibres. Diffusion of the polymer melting into the concrete matrix is impossible with this fibre; the diffusion process is thus blocked. Therefore, the use of this fibre offers an elegant way to test whether the other processes (PITS model, microcracks) make a contribution in addition to the diffusion of the polymer melting, because the demands on the fibres for the effectiveness of these other process models also still exist in the case of the highly cross-linked, infusible PE fibre. The fibre is hydrophobic, i.e. the important permeable boundary layer between the fibre and the concrete according to the PITS model must also exist here. The cross-linked fibre mass will also thermally expand on heating and, like the melt, will do so considerably more than the concrete. The following comparison of the linear thermal coefficients of expansion makes this clear: approx. 2 x 10-4 / K (for PE), approx. 1 x 10-4 / K (for cross-linked PE) [17] and approx. 0.1 x 10-4 / K (for concrete) [18]. That surprisingly bad result with this fibre – the amount of spalling is twice as high as with the 0-concrete – shows that no capillaries or microcracks are formed through which the steam can escape. The pore pressure is no longer relieved and the situation is thus similar to that with the 0-concrete without addition of fibres. In addition, the thermal expansion of the fibre mass causes thermo-mechanical stresses in the concrete, and increased spalling is the result.

Therefore, the only conclusion that can be drawn from these test results is that the reduction of the pore pressure by the melting of the PP fibres in the case of fire is exclusively a result of the diffusion of the polymer melting into the concrete. Other processes do not take place.
REFERENCES


