Contribution of polypropylene fibres melting to permeability change in heated concrete – the fibre amount and length effect

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Abstract. The paper presents the investigations related to concrete permeability change during heating and the contribution of polypropylene fibres melting at the temperature of 163°C to permeability. Permeability is an important parameter governing the occurrence of the explosive behaviour also known as concrete spalling due to fire. To limit the spalling of concrete, the polypropylene fibres are used to act as a fuse and, by melting, reduce gas pressure in concrete pore system. The investigations consisted of testing the permeability change of seven high performance concretes with polypropylene fibres. The permeability was measured after temperature exposure to temperature 140, 160, 180 and 200°C. The results have shown to what extent the fibre length and content affect the permeability when melting. Moreover the results have shown that the addition of polypropylene fibres had the desired impact causing a considerable increase in concrete permeability after fibre melting.

1. Introduction
The concrete infrastructure fires in tunnels (Mont Blanc tunnel, Chunnel tunnel) pointed at the problem of concrete explosive behaviour in fire which is known as fire spalling. Concrete spalling results mostly from thermal gradient within the concrete element, restraint of thermal strains and gas pore pressure increase in the concrete pore system. Low permeability cementitious materials like high-performance concrete (HPC) are characterised by low water-cement ratio and mineral additives incorporation. Those dense materials are particularly prone to spalling. One of the spalling prevention methods consists in the application of fibres that melt in the temperature lower than the temperature of maximum pore pressure occurrence, which is of 180-260°C [1]. Fibres melting temperature depends on the polypropylene (PP) type: for the low melting temperature polypropylene it is of 120°C, and for typical PP fibres is reaching 171°C. The PP fibres melting leads to favourable increase in permeability allowing the water vapour gas release. The study investigated various type of fibres: shorter 9 mm in length and longer 12 and 19 mm in length. In this study, two amounts of fibres were used 0.9 kg/m³ and 1.8 kg/m³. This amount corresponds to the amounts that are used commonly [2-4] to prevent spalling occurrence (0.1÷0.2% of concrete volume). Getting close to the melting temperature of fibres, melted polypropylene is absorbed by the cement matrix [1]. That is how a network of open pores, increases permeability, and consequently reduces the internal pressure in the heated concrete. However, the exact mechanism by which PP fibres work is still not fully explained. The increase of micro-cracking in heated concretes with PP fibres was observed. The presence of
fibres in the cement matrix may be considered as discontinuity that favours the initiation and development of micro-cracks during heating. On the other hand, fibres are expanding by 10% while melting what lead to crack development that contributes to an increase in concrete permeability.

2. Materials and methods

Seventy high performance concretes were designed with the same constituents apart of the fibre type and its amount. Corse basalt aggregates and Portland cement CEM I 52.5R were used. The concrete water-cement ratio was of 0.3, and it was obtained thanks to the plasticiser and superplasticiser application. The fibres for this research are produced in the fibrillation process consisting of cutting the polypropylene sheets into fibres with lengths of 6, 12 and 19 mm. The PP used in this research has a density of 0.91 g/cm$^3$. Three dosage levels 0; 0.9 and 1.8 kg/m$^3$ were used in tested concretes. The fibres melting temperature was of 163°C, and their burn-out temperature 360°C.

The compositions of all tested concretes are presented in table 1 while amounts of PP fibres used in research are indicated in table 2 for individual compositions.

| Table 1. Mix design of all tested HPCs. |
|----------------------------------------|
| Cement (kg/m$^3$) | Water (kg/m$^3$) | Sand 0/2 mm (kg/m$^3$) | Basalt agg. 2/8 mm (kg/m$^3$) | Basalt agg. 8/16 mm (kg/m$^3$) | Plasticizer (%mc) | Super Plasticizer (%mc) | w/c | Cement paste content (dm$^3$/m$^3$) | Mortar content (dm$^3$/m$^3$) |
|-------------------|------------------|------------------------|-----------------------------|---------------------------|------------------|-------------------------|----|-------------------------------|---------------------------|
| 490               | 145              | 611                    | 712                         | 712                       | 0.90             | 1.0 ± 2.0               | 0.30| 330                          | 514                       |

| Table 2. PP fibre dosage for individual tested HPC. |
|---------------------------------------------------|
| Length of fibre | HPC 0.9,6 | HPC 1.8,6 | HPC 0.9,12 | HPC 1.8,12 | HPC 0.9,19 | HPC 1.8,19 |
|-----------------|-----------|-----------|------------|------------|------------|------------|
| 6 mm            | -         | 0.9       | 1.8        | -          | -          | -          |
| 12 mm           | -         | -         | -          | 0.9        | 1.8        | -          |
| 19 mm           | -         | -         | -          | -          | 0.9        | 1.8        |

For permeability tests, cylindrical samples Ø150 mm and 50 mm high were used. The 28 days compressive strength was determined using 100 mm cubic samples. All samples were formed and cured in compliance with the PN-EN 12390-2 standard. After the 28 days compressive strength values are presented in the table along with the reference permeability.

The permeability tests were conducted after 90 days of curing and heating in the furnace with a constant rate of heating 1°C/min. Samples were heated from the ambient to the temperatures of 140, 160, 180 and 200°C and maintained at the target temperature for two hours. After cooling down the gas permeability using nitrogen was tested. Permeability was also established for the reference stage on samples dried to constant mass at a temperature of 105°C, according to the guidelines for the method applied described in RILEM Technical Recommendation [5]. Each measurement set comprised of three samples.

3. Results

3.1. Initial values of permeability and compressive strength

The compressive strength $f_{c,28}$ and permeability $k$ values are given in table 3. Considering the compressive strength test results, it may be concluded that this property does not vary considerably for
tested concretes. Slightly higher initial permeability values for fibres content of 1.8 kg/m$^3$ may be explained by the higher porosity of concretes introduced during mixing.

**Table 3.** Initial values of $f_c$ and permeability of concrete with and without PP fibres

| Label          | $f_{c28}$ (MPa) | $k$  ($m^2$) |
|----------------|----------------|-------------|
| HPC            | 106.5          | 5.451 x10$^{-17}$ |
| HPC_0.9_6      | 110.5          | 8.097 x10$^{-17}$ |
| HPC_1.8_6      | 111.0          | 7.220 x10$^{-17}$ |
| HPC_0.9_12     | 109.8          | 11.94 x10$^{-17}$ |
| HPC_1.8_12     | 108.0          | 15.00 x10$^{-17}$ |
| HPC_0.9_19     | 104.8          | 10.51 x10$^{-17}$ |
| HPC_1.8_19     | 101.0          | 52.89 x10$^{-17}$ |

3.2. Permeability change with temperature – influence of fibres length

It can be observed that an increase in heating temperature results in permeability increase, figure 1. The sharp permeability increase was observed between two measuring points at 140 and 160 °C. A significant increase in residual permeability takes place after heating to 160°C, thus to a temperature of 3 degrees lower than the melting temperature of the fibres used. This observation leads to a conclusion that the fibres are efficient even at temperature lower than melting temperature. This observation is in accordance with the observations of Kalifa [1] who reported the development of micro-cracks around the fibres. Nevertheless, the SEM observations suggest that the increase of permeability at this temperature may be caused by debonding of fibres from the cement paste. In figure 2 the contact zone between the cement paste and the surface of the fibre is presented.

For concrete without fibres (HPC) and concrete with a small addition of short fibres (HPC_0.9_6), this increase is relatively small. However, after heating to 200°C, the permeability increases three times. The addition of 0.9 kg/m$^3$ of fibres causes a significant increase in permeability for longer 12 and 19 mm fibres. At 160°C, the observed change in permeability reaches 6 and 12 times of the initial value.

![Figure 1. Change of relative permeability with temperature - influence of the length of the fibres.](image)

It can be also concluded that longer fibres after melting are more likely to form a percolated open pore system and contributing to existing porosity and adding to more porous interfacial transition zone (ITZ). The porosity increase of concretes with fibres in an amount of 0.9 kg/m$^3$ and length of 6; 12 and 19 mm, leads to permeability increase of 3; 11 and 24 times higher than initial. When the amount
of fibres was increased to 1.8 kg/m$^3$, a 45- and 50-fold increase in permeability was recorded for HPC with 12 and 19 mm long fibres respectively.

3.3. Permeability change with temperature – influence of fibre content
Based on the results presented in figure 4, it may be concluded that the amount of fibre strongly affects the changes in residual permeability caused by HPC heating. As expected, the highest increase in the residual permeability of heated concretes can be observed in samples in which higher fibre contents 1.8 kg/m$^3$.

Figure 2. SEM: x1000 PP fibre in concrete heated to temperature bellow melting. The deboning of fibre from the matrix.

Figure 3. SEM: x1000 PP fibre bed after melting and burning out of fibre, heating to 600°C. Visible micro-cracks.

Figure 4. Change of relative permeability with temperature - influence of fibres content.
4. Conclusions

On the basis of the presented results, the following conclusions can be drawn:

- The addition of polypropylene fibres in amounts of 0.9 and 1.8 kg/m³ does not affect strongly the initial properties of concrete. The compressive strength and permeability values have remained very close for all investigated concretes. Difficulties in homogenisation may have caused slightly higher values of permeability measured for concretes with greater PP fibres dosage.

- Increase in heating temperature results in progressive permeability increase mainly due to polypropylene fibres melting that occurs at 163°C. Nevertheless, the even lower exposure temperature of 160°C induced substantial permeability increase.

- The sharp permeability increase was observed between two measuring points at 140 and 160 °C. A significant increase in residual permeability takes place after heating to 160°C, thus to a temperature of 3 degrees lower than the melting temperature of the fibres used. The sharp permeability increase after exposure to 160 °C may be caused by partial absorption of fibres by cement matrix and due to debonding of fibres from the cement matrix.

- The length of PP fibres has a significant impact on permeability development. Short fibres seem to be not efficient in creating interconnected and permeable pore network. Although the total dosage of PP fibres was equal, the short fibres of 6 mm provide 4-fold lower permeability than fibres of 12 mm in length and 8-fold lower than 19 mm long fibres. It is concluded that except for increased porosity by melting of added fibres, the fibres melting can also build a connected network of micropores that can facilitate the moisture flow through the material.

- The amount of PP fibre plays a significant role in the development of permeability of concrete subjected to elevated temperature. It was observed that up to 140°C the results for different dosages are quite similar. Over this temperature, the impact of PP fibre dosage starts to differ. As spalling starts most frequently at temperature over 150°C, it is even more important to emphasize the influence of higher amounts of PP fibres on concrete permeability increase.

The increase of concrete permeability in fire situation in case of dense and tight concretes is vital for limiting concrete spalling propensity. The longer polypropylene fibres are proven solution enabling to increase permeability in an effective way. PP fibres provide a supplementary pore network at temperature lower than spalling occurrence, enabling gas pore pressure to be reduced. Therefore, the appropriate concrete mix design is of high importance, especially while designing the high performance concretes concrete structures with the risk of fire occurrence.

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5. References

[1] Kalifa P, Chéné G and Gallé C 2001 High-temperature behaviour of HPC with polypropylene fibers: From spalling to microstructure CemConcr Res 10 31 1487–99

[2] Han Ch-G, Hwang Y-S, Yang S-H and Gowripalan N 2005 Performance of spalling resistance of high performance concrete with polypropylene fiber contents and lateral confinement Cem Concr Res 35 1747–53
[3] Lo Monte F, Felicetti R and Rossino Ch 2015 In-plane loaded concrete slabs subjected to fire: a novel test set-up to investigate spalling Proc. IFireSS – International Fire Safety Symposium (Coimbra)

[4] Akasaka H, Ozawa M, Parajuli S S, Sugino Y, Akutsu Y and Murakami M 2018 Preventive Effect on Fire Spalling of High-Strength Concrete With Jute Fibre in Ring-Restraint Specimen 14th International Conference on Concrete Engineering and Technology (IOP Conf. Series: Materials Science and Engineering vol 431) 042001

[5] RILEM Technical Recommendation 1999 Tests for gas permeability of concrete, TC 116-PCD: Permeability of concrete as criterion of its durability Materials and Structures 32 174-79