THE MODE OF ACTION OF POLYPROPYLENE FIBRES IN HIGH PERFORMANCE CONCRETE AT HIGH TEMPERATURES

K. Pistol (1), F. Weise (1), B. Meng (1) and U. Schneider (2)

(1) BAM Federal Institute of Materials Research and Testing, Germany
(2) Vienna University of Technology, Austria

Abstract

It has been shown in fire tests that polypropylene fibres reduce or avoid explosive spalling of high performance concrete. In the critical temperature range up to 300 °C the permeability of HPC increases by using polypropylene fibre. Due to this the water vapour, which is the main reason for explosive spalling, can escape. There exist different theories in the literature concerning the micro structural mechanisms, which cause an increase in the permeability. Within the framework of an internal research project at BAM an innovative methodology was developed for experimental verifying of existing theories and to get new insights into this problem. The methodology used is unique and has been undertaken here for the first time. This consists of the combination of acoustic emission and ultrasonic measurement during temperature loading and the non-destructive micro structural analysis of cooled down samples with the aid of micro X-ray computed tomography. For the validation of the non-destructive test methods scanning electron microscopic images of prepared samples were undertaken. The results show that due to the thermal decomposition of the polypropylene fibres micro canals emerge. These are connected due to a simultaneous micro cack formation.

1. INTRODUCTION

In many publications concerning structural fire protection the advantageous behaviour of concrete in the case of fire is emphasised. As a result of its mineral consistence concrete is not combustible and, thus, does not contribute to the fire load. However, in recent decades reinforced concrete constructions have suffered extensive fire damage. This has occurred because modern high performance concrete (HPC) when exposed to high temperatures display explosive spalling. This leads firstly to a reduction in the cross-section and secondly to the exposing of the reinforcement. A result of this is the reduction of the load bearing capacity of the construction. Since the 1990s fine polymer fibres have been added to HPC to avoid explosive spalling in the event of fire. Within this process various types of polymer and fibre geometries have been used for verifying fire tests. As a result it has been ascertained that 1 to 5 kg/m³ polypropylene fibres (PP-fibres) are sufficient to avoid explosive spalling. These results have since been integrated into the European standard of structural fire design [1]. The damage mechanisms of explosive spalling, as well as the mode of action of PP-fibres, have still to be satisfactorily researched [2].

2. THEORIES ABOUT THE MODE OF ACTION OF PP-FIBRES

Since it has become common knowledge that PP-fibres are suitable for fire safety design a variety of theories concerning the mode of action of PP-fibres have been suggested. Most of the authors presume that the density of HPC prevents the vapour flow which is the main
cause of explosive spalling. This is why theories concerning the mode of action of PP-fibres are described as permeation theories. These authors are in agreement on the presumption that due to the thermal decomposition of the PP-fibres the permeability of concrete is increased and a transport system is provided for the emerging water vapour [3]. However, only a small number of researchers have examined the creation of this transport system. In the following summary different hypothesis will be categorized and discussed in relation to the existent literature, but not in an exhaustive fashion, rather a summarizing overview will be given.

2.1 Formation of micro canals due to thermal decomposition of the fibres

A supposition common within specialist circles presumes that due to the melting of the PP-fibres at 170 °C micro canals emerge and become available for the transport of the water vapour. However, thermal analysis shows that the thermo-oxidative decomposition of polypropylene occurs between 200 and 300 °C. There has not been, until now, any existent knowledge of the thermal decomposition of PP-fibres in concrete, nor of the interaction between cement matrix and the PP-fibre melt. Kalifa et al. [4] assume that the fibre melt penetrates into the cement matrix, while Khoury [5], on the other hand, is of the opinion that the high viscosity and the molecule size suggest otherwise.

2.2 Permeable transition zone between fibre and cement

Because the free and physically bounded water vaporizes at temperatures more than 100 °C, it must be assumed that the permeability is increased by the application of PP-fibres just before the melting of the fibres. Bentz [6] proffers a theory of percolation which presumes that porous interfacial transition zones (ITZ) emerge around the PP-fibres and, thus, the ITZs between cement matrix and aggregates are connected. This theory has been adopted by numerous researchers, yet it has not been experimentally confirmed. Khoury [5] also presumes that just before the melting of the PP-fibres a permeable transition zone between the fibre and cement comes about. His supposition is that the hydrophobic fibres are released from the cement matrix due to the vapour pressure and, thus, a „pressure-induced tangential space“ (PITS) becomes free.

2.3 Formation of micro cracks

Kalifa et al. [5] undertook microscopic analysis of samples after a temperature treatment of 400 °C and concluded that the sample with PP-fibres contained a net-like micro crack structure and the fibre-free sample in contrast held less cracks with larger crack widths. Larbi And Polder [7] and Liu et al. [8] have confirmed this in recent studies. It has not however been systematically examined under what temperature the crack formation takes place and how the crack formations propagate the concrete.

3. AIM OF THE STUDY

The above mentioned different hypothesis concerning the mode of action of PP-fibres in HPC at high temperatures are partly contradictory or have not been experimentally proven. The aim of the study is to examine the existing theories to the extent where this is possible and to produce new forms of knowledge with the help of an innovative methodology. The main focus of the studies to be described is the monitoring of the crack formation processes in the temperature range of the thermal decomposition of the fibres and the spatial visualization of the crack structures in thermal loaded specimens.

4. APPROACH

In order to acquire new forms of knowledge regarding the crack formation processes in thermal loaded HPC, with particular attention to the influence of PP-fibres, a new and innovative examination methodology was developed at BAM. This consists of the
combinations of acoustic emission and ultrasonic measurement during temperature loading and the non-destructive micro structural analysis of cooled down samples with the aid of micro X-ray computed tomography. For the validation of the non-destructive test methods additional scanning electron microscopic images of prepared samples were undertaken.

5. MATERIALS

In the study, PP-fibres with a diameter of 32 µm (7 dtex) and a length of 6 mm were used. In the investigations a HPC was created with a compressive strength of 110 MPa (with 2 kg/m³ PP-fibres) and 113 MPa (without PP-fibres) measured at cylindrical specimens (diameter: 100 mm, height: 300 mm). The Specimens were stored after demoulding for six days in water and thereafter in a climate chamber at 23 °C and 50 % relative humidity for a minimum of 160 days. The proportions of the mixtures are given in Table 1.

Table 9: Mix design of HPC

<table>
<thead>
<tr>
<th>components [kg/m³]</th>
<th>HPC-PP</th>
<th>HPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>cement CEM I 42,5 R</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>water</td>
<td>173</td>
<td></td>
</tr>
<tr>
<td>aggregates (siliceous)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2 mm</td>
<td>769</td>
<td></td>
</tr>
<tr>
<td>2-4 mm</td>
<td>231</td>
<td></td>
</tr>
<tr>
<td>4-8 mm</td>
<td>538</td>
<td></td>
</tr>
<tr>
<td>silica fume</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>superplasticizer</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>PP-fibres</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

6. RESEARCH METHODS

6.1 Thermomechanical test bench with acoustic measurement technology (AE/US)

Cylindrical specimens (diameter: 100 mm, height: 300 mm) with and without PP-fibres were heated with a rate of 1 K/min in a thermo-mechanical testing machine until 750 °C. The test setup is described in [9]. For the monitoring of the crack formation in the specimen during the temperature loading an acoustic emission (AE) system was applied. An assembly scheme and the AE-setup are illustrated in Figure 1. The measuring principle is based upon the fact that crack formation generates sudden material displacements, which propagate as elastic waves. With the aid of scale-free wave guides of steel it is possible to register the waves at the surface of the specimen. Piezoelectric sensors transform the waves into electric signals. Thereby the number of the AE-events allows a quantification of the crack formation process. At BAM a commercial AE-system (Vallen AMSY-5) has been used. This system facilitates the simultaneous measurement of the US time-of-flight in the specimen by using the sensors as pulse sensors.

6.2 Micro X-ray 3D computed tomography (µX-3D-CT)

For the spatial visualization of the structural changes the micro X-ray 3D computed tomography (µX-3D-CT) was utilized. The measurement principle of µX-3D-CT is based on the radiography of the specimen from various angles of observation of the whole circumference of the object. The process of measuring itself is based upon the different weakening of the X-ray radiation due to differences in density and thickness in the object being examined (Figure 2). Weise et al. [10] have described the measuring principle and the analytic possibilities of µX-3D-CT. To detect the PP-fibres and to monitor the crack formation small drilled cores (diameter: 12 mm, height: 100 mm) were used. The cores were heated to different temperature steps (200 °C, 250 °C and 300 °C). For every temperature the cores were tomographically analysed after they had cooled down.
6.3 Scanning electron microscopy (SEM)

For the validation of the non-destructive test methods scanning electron microscopic (SEM) images of prepared samples were undertaken (Figure 3). Contrary to the µX-3D-CT for every temperature step another sample is needed. A SEM-image is generated by scanning the surface of samples with a beam of electrons. If the electrons strike the surface they interact with the atoms and are then scattered. In principle there exist two types of scattered electrons: secondary electrons (SE) and backscattered electrons (BSE). SE have a lower energy level than BSE and are ejected by inelastic scattering within a few nanometres from the surface of the sample. They produce high-resolution images. In this study, SE-images were taken from fractured surfaces of heated and cooled down samples. Thus, the morphology of the PP-fibres in its environment could be detected. The intensity of the BSE-signal depends upon the atomic number of the element in the scanned area. The contrast of BSE-images can provide, in this way, the analysis of pores and cracks. For this, further samples were sawed and placed into resin after cooling. After the hardening of the resin the samples were rubbed and polished with diamond paste. Then BSE-images were taken from these polished sections for verifying the µX-3D-CT.

7. RESULTS AND DISCUSSION

7.1 Temperature-dependent crack formation

In Figure 1 the number of acoustic emission events is plotted against the temperature for the HPC with and without PP-fibres. It can be seen that the PP-fibres led to a higher amount of crack formation. The results show a clear increase in the number of events as the temperature rises. The use of PP-fibres significantly reduces the number of events, indicating their effectiveness in improving the temperature resistance of the concrete.
of AE-events in the temperature range between 200 °C and 300 °C with a peak of 250 °C. Also the US time-of-flight increases in this temperature range. This confirmed the conclusion regarding the increased crack formation in PP-fibre reinforced concrete.

7.2 Non-destructive visualisation of the microstructure
With the aid of µX-3D-CT it is possible to get a non-destructive visualisation of the microstructure. At first the initial state (20 °C) of the specimen was tomographically documented. Figure 2 indicates a selected virtual horizontal cross-section of the spatial absorption image of the drilled core, consisting of HPC with PP-fibres. In this absorption image light coloured areas represent areas with a low radiographic density, while dark areas represent those of a high radiographic density. In this way the aggregates and the cement are depicted in light grey shades, while PP-fibres and cracks appear in darker shades. For the verification of the crack formation due to thermal load the specimens were heated at various temperatures. After cooling the µX-3D-CT was performed. Comparative observation of a detail of the absorption image of the untreated and the heated drilled core in the same virtual horizontal cross section height, shows first micro cracks at 200 °C and a significant crack formation at 250 °C. Furthermore, it is noticeable that the cracks mostly go through the fibre regions. At 250 °C the PP-fibres are already melted so that in these spaces micro canals emerge (see Figure 3: SE-image). From the area of damage mechanics we know that in the edges of such areas of discontinuity higher stresses than in undamaged areas occur. This leads to an initiation of crack formation in these edges.

![µX-3D-CT-setup](image)

![Results and experimental setup of the µX-3D-CT](image)

Figure 25: Results and experimental setup of the µX-3D-CT
7.3 SEM analysis of the microstructure

A more precise analysis of the crack formation was undertaken with further SE-images of fractured surfaces. Figure 3 shows specific SE-images of the fibre area of differently heated samples. Especially interesting is the image created after the temperature treatment at 200 °C. It shows on the right side a shrunken PP-fibre located in its original fibre bed. On the left hand side of the same image an “empty” fibre bed is to be seen within which the PP-fibre has
been torn out by the sample preparation. The images of the samples which were heated at 250 °C and 300 °C show that a significant crack formation at the edges of the micro canals was created after the melting of the PP-fibres, especially in the longitudinal direction. The micro canals and the cracks build a filtration system for the emerging water vapour in the event of a fire.

With the aid of BSE-images the results of the 3D-CT were validated. The BSE-images of selected areas displayed in Figure 3 indicate the same results as seen in the absorption images of the µX-3D-CT in Figure 2. A propagation of cracks in samples heated at 200 °C is to be observed here as well. In addition to this the interconnection of micro cracks and micro canals in the concrete micro structure can be seen.

8. CONCLUSIONS AND OUTLOOK

With the help of AE/US-measurements, µX-3D-CT and SEM it has been shown that after the melting of the PP-fibres at 170 °C micro canals arise, which function as “wanted” micro spaces in the concrete micro structure. The micro canals represent damage mechanical defects at whose edges crack formations are initiated. The micro canals and the cracks build a filtration system for the emerging water vapour in the event of a fire.

These results contribute to the answering of the question under what temperature the crack formation takes place in heated PP-fibre reinforced HPC and how the crack formations propagate the concrete. However, there are still many unanswered questions concerning the mode of action of PP-fibres in HPC at high temperatures. The following problems will be amongst others the subject of further investigations:

- penetration behaviour of the fibre melt into micro cracks / cement matrix
- determination of the permeability of PP-fibre reinforced HPC at high temperatures

ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. Jürgen Goebbels and Dietmar Meinel who carried out the µX-3D-CT. Their “non-destructive” work allowed us to study the crack formation in thermal treated concrete without any sample preparation. This contributed to the view of microstructure presented in this paper.

REFERENCES


[2]