PERMEABILITY OF CONCRETE AT HIGH TEMPERATURES AND MODELLING OF EXPLOSIVE SPALLING

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Abstract: Durability of concrete is mainly influenced by its permeability. High performance concrete (HPC) is generally considered to be a highly durable material, owing mainly to its low permeability. However, when exposed to fire, HPC is highly vulnerable to the phenomenon of explosive spalling. The transport of fluids inside concrete is hindered by low permeability of HPC. Permeability measurements on concrete are mainly performed at room temperature, only scarce information is available on permeability of HPC at elevated temperatures. In the present paper, a new test setup for permeability measurements at elevated temperatures is presented. Two different types of concrete, namely plain HPC and HPC with 1kg/m^3 of polypropylene fibres, were tested up to temperatures of 300°C. It was observed that the melting of fibres is not the only reason for the prevention of explosive spalling. Additionally, experiments were conducted on 700x700x300 mm^3 slabs in order to investigate the performance of HPC without and with PP fibres. Furthermore, using the thermo-hygro-mechanical model for concrete the phenomenon of explosive spalling was numerically investigated. Influence of permeability and relative humidity on various aspects of explosive spalling was investigated and the findings are reported.

1 INTRODUCTION

Explosive spalling of HPC under fire is one of the major concerns in front of the engineering community today. It is associated with violent failure of thin layers of concrete resulting in sudden reduction of load carrying capacity, which may lead to complete collapse. High pore pressures due to low permeability and stresses due to thermal gradients are considered to be the governing causes of explosive spalling [1-2].

The most popular method to prevent spalling is the addition of polypropylene (PP) fibres in concrete. It is widely accepted that the PP fibres leave a porous network after melting at around 160°C, leading to an increase in permeability, thus allowing the water vapour to escape [3-4]. The influence of elevated temperature on permeability of concrete is well documented in the literature [3-6]. However, the majority of these tests have been performed on concrete in residual state, i.e. after the specimens were cooled to the room temperature.

This work is aimed at investigating the effect of permeability on explosive spalling of HPC by means of experiment and numerical analysis. A new test setup for permeability measurements at elevated temperatures was developed and validated against the RILEM CEM-Bureau method [7]. HPC without and with PP fibres was tested at temperatures ranging from 20°C to 300°C. The tests were helpful in observing and understanding the beneficial effect of addition of PP fibres in mitigation of explosive spalling. The concrete slabs made of same batch of concrete were exposed to ISO 834 fire, and it was observed that concrete without fibres experienced severe spalling, whereas concrete with PP fibres suffered negligible damage.

The numerical modelling of explosive spalling was performed employing the thermo-hygro-mechanical model for concrete developed in the framework of three dimensional finite element program MASA [8-9]. The modelling was performed at meso-scopic level, where the concrete was modelled as a three phase material comprising coarse aggregates, cement mortar and interfacial transition zone. The influence of permeability and relative humidity on explosive spalling was evaluated. It was observed that higher relative humidity and lower permeability result in an increased risk of explosive spalling.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Permeability measurements at high temperature

A new test setup for measurement of permeability at elevated temperatures was developed and the same is shown in Figure 1. Specimens used in these tests were hollow cylindrical specimens (ring-shaped), which were placed between two steel plates. A graphite sealant with dimensions corresponding to the geometry of the specimen was placed between the plates and the specimen. The setup was insulated using cooling and insulating plates. The applied load was monitored employing a 500 kN capacity load cell. The steel frame consisted of two stiff plates and four steel rods. The load was monitored throughout the experiment using a commercial data acquisition software Diadem [10]. The specimen was heated using a spiral heating collar fastened to the rods.

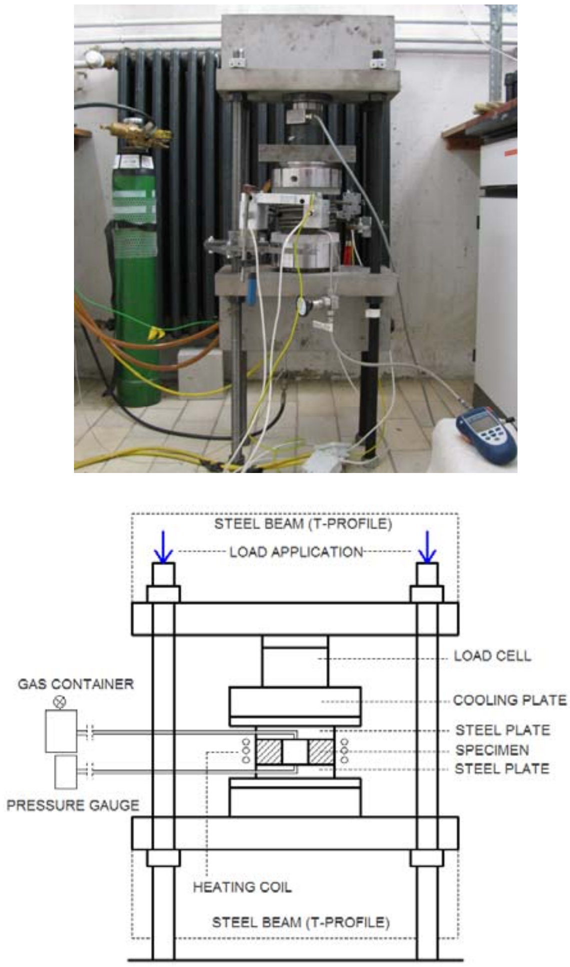

Figure 1: Test new test setup for the permeability measurements at elevated temperatures.

Around the heating collar, a heat resistant insulation was applied in order to minimize the heat loss to the environment. Temperature was measured and controlled throughout the experiment in steel plates using thermocouples. A heating rate of 0.5°C/min was selected to avoid possible cracking due to thermal gradients. The gas container was connected to the gas inlet and the gas outlet was connected to the pressure gauge. Nitrogen was used as permeating gas, owing to its inert behaviour with respect to concrete and since it does not enhance burning.

Once a pressure of 20MPa was applied, the initial permeability measurement was performed at the room temperature. The hollow portion of the specimen was pressurized using nitrogen and the pressure was measured. Maximum applied pressure was 11 bar, while the minimum was 2 bar (both gauge pressure). The pressure history was obtained and apparent permeability for every time step was calculated using the following expression derived from Darcy's and Clapeyron's law:

$$k = \frac{\eta ln(\frac{r_2}{r_1})}{\pi H} \frac{\frac{\Delta p}{\Delta t} V}{(p_2^2 - p_1^2)} \tag{1}$$

Where: k [m^2] = permeability, η [Ns/m^2] = viscosity of the permeating fluid, r_1 = inner radius of the specimen, r_2 = outer radius of the specimen, H [m] = height of the specimen, p_1 [Pa] = inlet pressure, p_2 [Pa] = outlet pressure (atmospheric pressure), V [m^3] = volume of the pressurized gas. In each time interval Δt, the apparent permeability k is calculated according to Eq. (1). Pressure decay history was obtained from the experiment. Intrinsic permeability was evaluated employing the Klinkenberg method [11].

In case of specimens tested at elevated temperature, once the specimen attained the desired temperature, three or more permeability tests were performed following the above-described procedure and the specimen was heated to the next target temperature. The permeability measurements in case of specimens without fibers were carried out at temperature levels: 20°C, 80°C, 150°C and 200°C. A few more measurements were made in case of specimens with fibres to cover the region around the melting point of fibers, i.e. measurements were also performed at 130°C and 170°C.

Upon finishing the test series at elevated temperatures, the specimen was gradually cooled to the room temperature to prevent high temperature gradients. Residual permeability measurements were performed after the specimen was kept at room temperature for at least 12 hours.

High performance concrete (grade C80/95) without and with PP fibers with a maximum aggregate size of 8 mm was used. The cubic compressive strength at the time of testing was approx. 90MPa. Concrete with PP fibres contained 1kg/m^3 of fibres.

Specimens were prepared by core cutting from the slab and were cut into pieces of required height. Hollow cylindrical specimens with inner radius, r_1 of 40mm, outer radius, r_2 of 120mm and height, H of 40mm were used. Top and bottom surface of the specimens were then polished to ensure that the surfaces are smooth and parallel.

Prior to testing, all specimens were subjected to thermal preconditioning by drying in oven at 60°C until constant mass was reached, i.e. less than 0.5% variation of mass during 24 hours. Very moderate drying temperature is opted for to prevent any cracks that might influence the permeability of concrete.

In this study, PP fibers with a diameter of 15.4µm and a length of 6mm were used. The fibers were extruded from pure PP with following material properties: mass density 910kg/m^3, tensile strength 241N/mm^2, Young's modulus 573N/mm^2, maximum (limit) strain 250%. Fibers lose the thermal stability at 120°C, melt at approximately 160°C and burn at 320°C. The viscosity of the fibers was very low with a melt flow rate (MFR) greater than 1000g/10 min, which makes them much more effective as compared to the standard fibers (MFR = 30g/10min). The fibers were mixed with aggregates and cement before the water was added to ensure even distribution of fibres throughout the specimen.

Sealing of the specimen was achieved using fire resistant graphite sealant. Due to the sensitivity of graphite to oxidation, the gas employed in the permeability tests was nitrogen. In order to reach the desired permeability of graphite (few orders of magnitude lower than the lowest concrete permeability), it was required to apply a pressure of at least 15MPa. Pressure of the order of 20MPa was applied during the test.

2.2 Experimental results on permeability

The relation between measured permeability and temperature for the two investigated concrete types is plotted in Figure

2. It can be observed that concrete without addition of PP fibers displayed a steady rise in permeability with increasing temperature. The average permeability for plain concrete at 20°C was obtained as 2.6×10^{-18} m^2. It was observed that up to 80°C there was no significant increase in permeability. Beyond 80°C, there was almost a linear increase in permeability with rise in temperature (semi-log scale). After reaching a temperature of 200°C, permeability increased by approximately 20 to 30 times, whereas at 300°C there was an increase in permeability of two orders of magnitude as compared to the value at room temperature. Since no visible surface cracking was observed upon finishing the heat treatment, it could be concluded that the increase of permeability was primarily due to the change in the internal porous system of concrete, i.e. the percentage of larger pores was increased as well as total porosity [12]. Residual values obtained on specimens cooled to the room temperature are approx. 10-25% higher than the values obtained at the elevated temperatures.

In case of concrete with PP fibers, at temperatures up to 80°C the permeability was found to be very similar to the concrete without fibers. Therefore, it can be stated that the addition of PP fibers does not significantly influence the permeability of concrete at temperatures up to 80°C. However, at temperatures above 80°C concrete with fibers exhibits a sudden jump in permeability of almost two orders of magnitude (Figure 2). At 150°C, the difference between the two concrete types is almost two orders of magnitude. Beyond 170°C, the rate of permeability increase roughly corresponds to that of concrete without fibres. Same as in case of concrete without fibres, the residual permeability values of concrete with fibres were found to be higher than the permeability values at elevated temperatures.

These experiments clearly demonstrated that there is a significant increase in the permeability of concrete with PP fibres in temperature range between 80°C and 130°C. This is considered to be the major reason for the beneficial effect of addition of PP fibres in mitigation of explosive spalling.

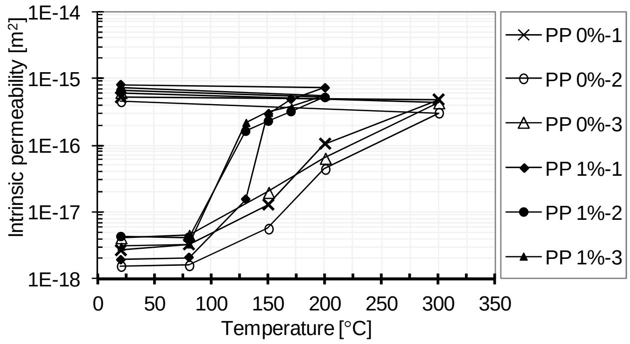

Figure 2: Intrinsic permeability of concrete as a function of temperature.

It is generally considered that the empty fibre beds form an interconnected network of empty pores and lead to a rise in permeability. However, these experimental data show that the permeability increase takes place at temperatures much lower than the melting point of fibres (160°C). Hence, the results suggest that the melting of fibres is not the only mechanism responsible for the permeability increase. Fibres lose their thermal stability at around 120°C, which results in a significant decrease in elasticity modulus. They become softer and more susceptible to change of shape. One of the possible explanations for the sudden rise in permeability is that the pressurized gas compresses fibres and creates a path between concrete and fibre surface.

2.3 Experiments on slabs exposed to ISO 834 fire

In order to understand the phenomena of explosive spalling and the influence of addition of PP fibers on the same, experiments were performed on 700x700x300 mm^3 slabs made of concrete without and with PP fibres. The tests were conducted by the authors along with other researchers from University of Munich, under the collaborative project. The slabs were cast from the same batch of concrete from which the specimens for permeability tests were obtained.

The specimens were exposed to ISO 834 fire on one large face (700x700mm^2). Three specimens for each type of concrete were tested simultaneously. Two fire burners were employed in order to heat the oven.

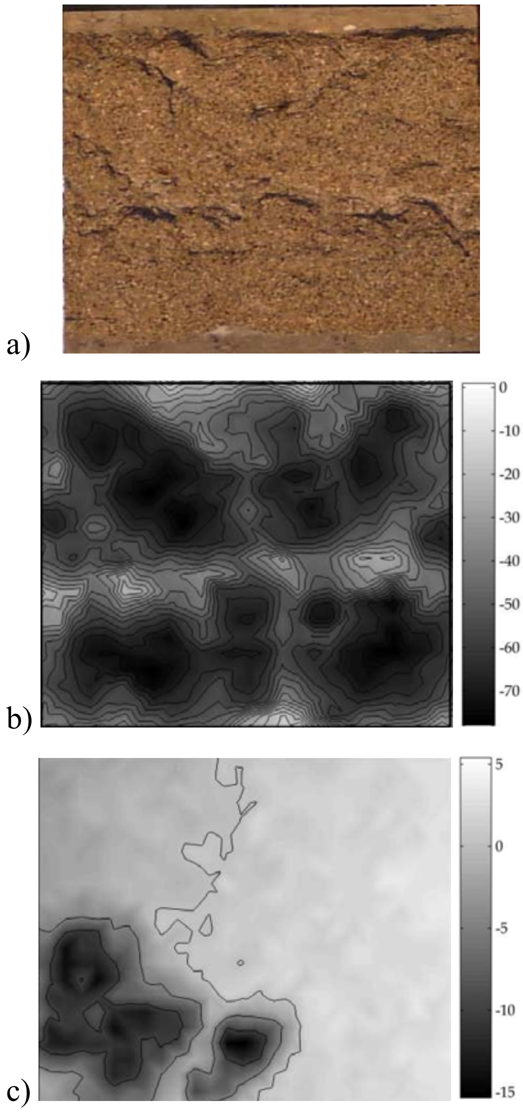

Figure 3: Explosive spalling observed in the tests: (a) plain HPC, (b) spall depth contours [mm] for plain HPC, and (c) spall depth contour [mm] for concrete with PP fibres.

It was observed that the explosive spalling of the plain HPC initiated after approx. 8 minutes of exposure. It was associated with forcible separation of thin layers of concrete accompanied by a loud sound. Successive failure of thin layers finally led to a significant reduction of the slab cross section. All three tested specimens suffered very extensive spalling and the test was stopped after 30 minutes in order to avoid a complete collapse of the slabs. The maximum spalling depth was observed to occur approx. above the burners, indicating the contribution of non-uniform heating to the extent of explosive spalling. Figure 3 presents: (a) the specimen without PP fibres after completion of the test and the corresponding spall depth contours [in mm] for (b) plain concrete and (c) concrete with PP fibres. It can be observed that significant amount of spalling occurred in the case of plain HPC specimen and up to 70mm spall depth was measured.

On the other hand, concrete with PP fibres experienced almost no explosive spalling (one of the three tested specimens exhibited minor spalling). However, both concretes experienced significant cracking due to thermal stresses. Nevertheless, the experiments clearly demonstrated that PP fibres are very effective in prevention of explosive spalling of concrete.

3 NUMERICAL MODELLING OF EXPLOSIVE SPALLING

Experiments clearly demonstrated certain aspects of explosive spalling. However, only limited information could be deduced due to the inherent difficulties in such experiments. On the other hand, numerical analysis can provide much more detailed insight into the problem. In this work, the problem of explosive spalling was numerically analyzed employing the thermo-hygro-mechanical (THM) model with temperature dependent microplane model as constitutive law for concrete [8-9]. The concrete was discretized as three phase material comprising of coarse aggregates, cement mortar and an interfacial transition zone between the two. Under assumption of plane strain condition, a slice of a concrete specimen was simulated. The advantage of symmetry was taken. The geometry and the boundary conditions are shown in Figure 4.

The analysis was carried out for different values of relative humidity (RH) viz. 20%, 40%, 70%, 85%, 92% and 100%. The typical failure mode corresponding to 70% RH is shown in Figure 5. One can observe that the failure occurs locally and at a relatively low depth, typical to the phenomenon of explosive spalling.

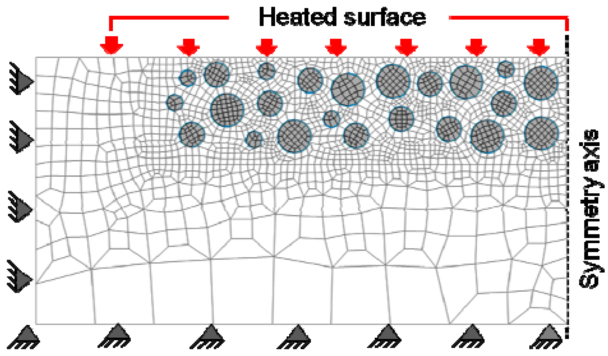

Figure 4: Geometry and boundary conditions.

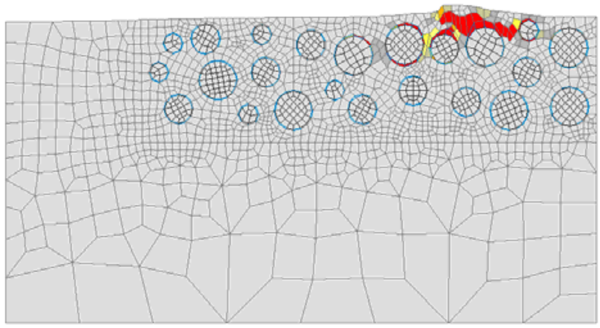

Figure 5: Failure mode corresponding to 70% RH.

The development of pore and volumetric pressure in the critical element with time is shown in Figure 6. The pore pressure is calculated using the THM model, while the volumetric pressure is derived by multiplying the pore pressure with the porosity [8]. It can be observed that the onset of explosive spalling is demarcated with a sudden increase in the rate of development of volumetric pressure (Figure 6).

The series of analyses were evaluated to obtain the influence of relative humidity on (i) strain rate at failure; (ii) time of initiation of exp. spalling; and (iii) volumetric pore pressure corresponding to the onset of explosive spalling.

Figure 7 displays the variation of strain rate with increasing relative humidity. In the case of rel. humidity less than approx. 60%, the failure strain rate is rather small, indicating cracking mainly due to thermal stresses. On the other hand, for RH above 60% much higher values of failure strain rates were obtained, which is associated with the violent nature of explosive spalling.

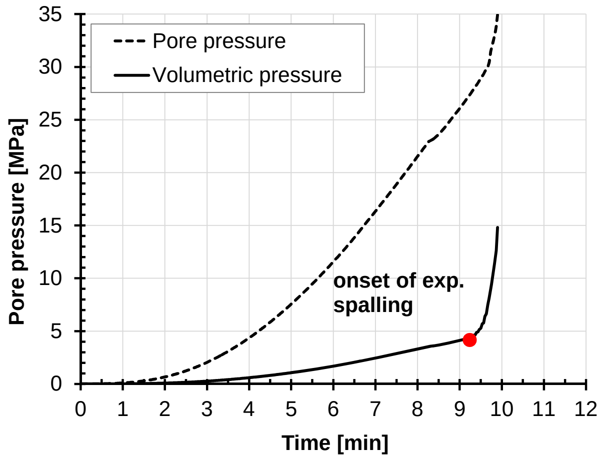

Figure 6: Development of pore and volumetric pressure in the critical element with time.

The influence of relative humidity on time of spalling is plotted in Figure 8. The time of spalling was almost constant for RH less than 60%, whereas it decreased rapidly for RH above 60%. Together with findings shown in Figure 7, it can be concluded that the failure mechanism for RH less than 60% can be mainly attributed to non-explosive spalling caused by thermal stresses.

Both the findings are consistent with the available experimental data [13], which showed that higher relative humidity enhances explosive spalling. Concrete specimens with very low moisture content exhibited no explosive spalling.The variation of volumetric pressure at failure with respect to relative humidity is shown in Figure 9.

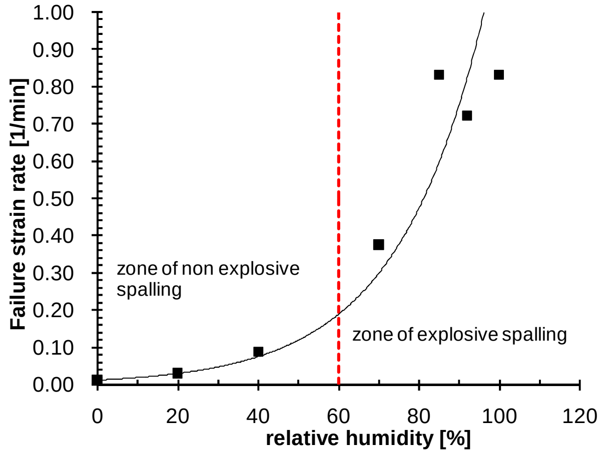

Figure 7: Variation of failure strain rate with RH.

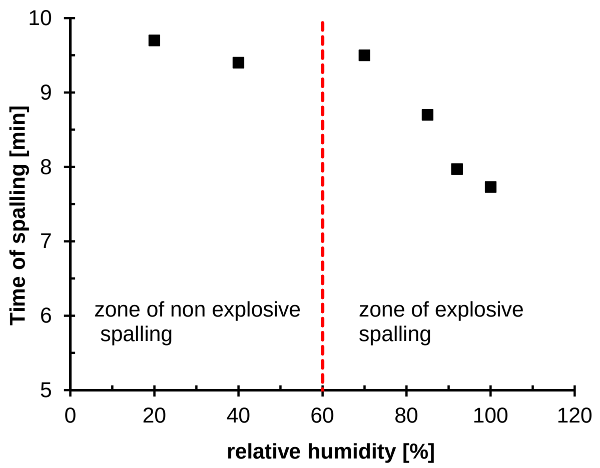

Figure 8: Variation of time of spalling with RH.

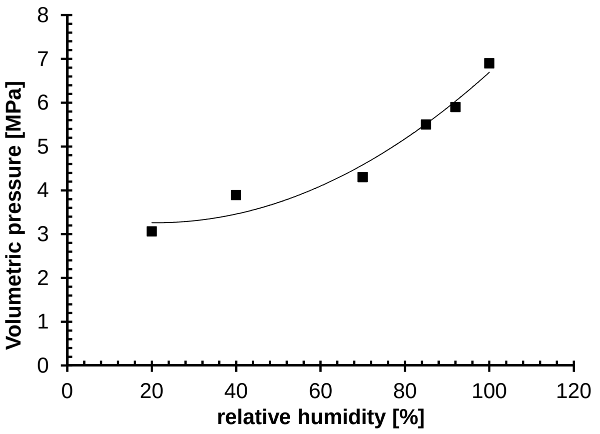

Figure 9: Variation of volumetric pressure at failure with RH.

A gradual increase of the failure volumetric pressure is observed. Since the volumetric pressures at failure change with relative humidity, it can be inferred that a certain level of thermal stresses is essential for explosive spalling. Pore and volumetric pressures act as a trigger to explosive spalling and only the combination of these with thermal stresses can lead to explosive spalling. Further analysis of the same example with the thermo-mechanical model [14] instead of the THM model confirmed that the thermal stresses alone can result only in non-explosive type of spalling.

4 CONCLUSIONS

In this work the phenomenon of explosive spalling was experimentally and numerically investigated, with emphasis on permeability and relative humidity. A new experimental setup for measuring permeability of concrete at high temperature is presented. It was employed in the measurements of permeability of HPC without and with PP fibres (1kg/m^3) at temperatures ranging from 20°C to 300°C. Plain HPC exhibited a steady increase in permeability with rising temperature, whereas HPC with PP fibres experienced a very sudden increase in permeability at temperatures between 80°C and 130°C. Due to the sudden rise in permeability, the water vapour can escape thus leading to prevention of explosive spalling. Furthermore, these results indicated that the melting of fibres may not be the only mechanism leading to the sudden rise in permeability, since fibres melt only at 160°C.

Experiments were also carried out on 700x700x300mm^3 slabs subjected to one-sided heating as per ISO 834. Significant amount of explosive spalling was observed in case of plain HPC, whereas HPC with PP fibres exhibited only very limited spalling.

To further investigate the phenomenon of explosive spalling, numerical analysis was performed at meso-scopic scale employing thermo-hygro-mechanical model. Explosive spalling could be simulated well using this approach. The influence of relative humidity on explosive spalling was investigated in detail and it was found that the increase in RH leads to a higher risk of explosive spalling. With increase in RH, explosive spalling tends to occur earlier. Below RH approx. 60% the probability of occurrence of explosive spalling is rather low, while beyond 70% there is a high risk of the occurrence of explosive spalling.

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