COMBINED ACOUSTIC EMISSION AND SIMULATION APPROACH TO STUDY FRACTURE BEHAVIOR OF CONCRETE UNDER FIRE LOAD

Christian U. Grosse*, Ronald Richter* and Joško Ožbolt†

* Technische Universität München
Non-destructive Testing, Center for Building Materials, Munich, Germany
e-mail: grosse@tum.de, web page: http://www.zfp.tum.de

† Universität Stuttgart
Institute of Construction Materials, Stuttgart, Germany
e-mail: ozbolt@iwb.uni-stuttgart.de, web page: http://iwb.uni-stuttgart.de

Key words: Concrete, Spalling, Fire, Acoustic Emission, Ultrasound

Abstract: Following the recent developments in civil engineering there is a clear trend to involve more and more innovative materials like high performance concrete (HPC). HPC is often used for tunnel lining, for columns of high raise buildings and similar structures, which require high compressive strength. However, when exposed to high temperature (fire) there is a strong degradation of mechanical properties of HPC and it shows unfavorable behavior, i.e. explosive spalling of concrete cover.

In the here discussed experiments the behavior of concrete specimen that were exposed to fire is monitored by acoustic emission (AE) technique. Using this technique it is possible to observe damage processes in concrete during the entire fire history. It is in particular possible to detect the initialization of explosive spalling. The article describes the proposed concept and preliminary results of fire experiments on concrete specimens made of HPC with and without addition of polypropylene fibers. To better understand the experimental results it is also important to employ a numerical model, which is able to realistically predict the behavior of concrete at high temperature including transport of moisture and the role of pore pressure in concrete exposed to elevated temperature. Therefore, a fully coupled thermo-hygro-mechanical model for concrete was implemented into a 3D finite element code [1, 6, 7]. The application of the model demonstrates that the pore pressure in combination with thermally induced stresses is the main reason for explosive spalling of concrete cover. The addition of polypropylene fibers is resulting in a drastic decrease of the risk for explosive spalling. This is proved by the simulation as well as by the experimental results including acoustic emission analysis and ultrasound [2]. It is shown that the addition of polypropylene fibers caused increase of permeability of concrete for more than two orders of magnitude, which significantly reduces risk against explosive spalling.

1 INTRODUCTION

Experimental fire investigations are difficult and expensive. So there are often limitations to carry out full-scale tests. But they are very important to understand the process of high performance concrete spalling under fire exposure. So it is useful to get as most information out of an experiment as possible. So a possibility for measurement and documentation of the time cause of the damages is needed. This can be done by using acoustic emission (AE) and other non-destructive testing techniques [5]. An experimental setup was developed being able to observe the initial micro-cracking process and the time development of spalling. AE techniques can deliver data directly related to deteriorations and are an appropriate validation tool [3, 4].

The data will be compared with numerical simulations because it is another way to investigate the concrete behaviour and the time development. To achieve realistic results enabling for valid material prognoses a calibration of the used models and model parameters is required.

The experimental setup setup and some preliminary results of two experiments with HPC are shown in the following chapters additional to some results of the numerical simulation.

2 SETUP AND EQUIPMENT

Experiments with two different temperature curves were tested, one time with the ETK and a second time with the modified ZTV-Ing curve (Figure 1).

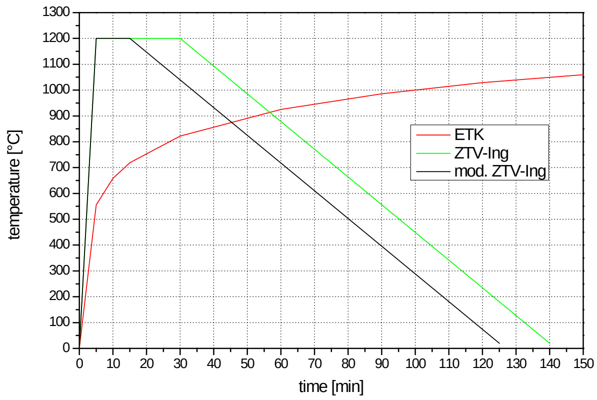

Figure 1: Temperature evolution inside the furnace chamber.

On every temperature curve two different HPC mixtures were tested, one with and one without polypropylene (PP) fibers. The setup and measurement equipment for both experiments were the same. In the following only the experiments with the higher ZTV-Ing curve are described. The results of the ETK experiments are presented in another paper [2].

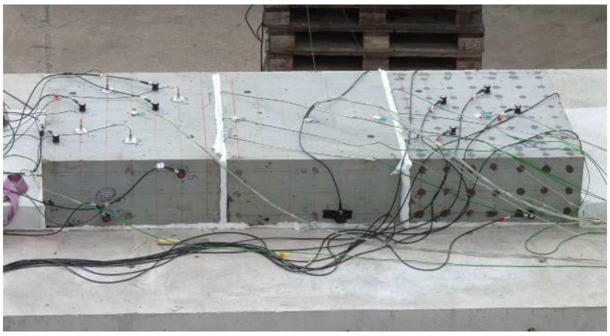

Figure 2: HPC specimens with AE-sensors on top of the furnace and the position of Ultrasonic Senor.

Figure 3: Furnace with four burners on both sides.

For the fire experiments an oil-burner-furnace at the MFPA Leipzig was used (Figure 3). To introduce the fire condition in the furnace there were eight oil-burners through openings on two sides of the furnace. The furnace was equipped on the top with three HPC test specimens with a size of 70x70x30 cm3. Figure 2 and Figure 3 show the experimental setup.

Two of the three specimens were monitored with acoustic emission sensors (Figure 4). A temperature monitoring device inside the specimens and the furnace chamber was important to control the furnace and to get information about the temperature development during the experiments.

Figure 4: Acoustic emission sensors used on two specimen on top of the furnace.

3 RESULTS

In the experiments with specimen without PP-fibres it was possible to see the spalling of the HPC after a few minutes (Figure 5).

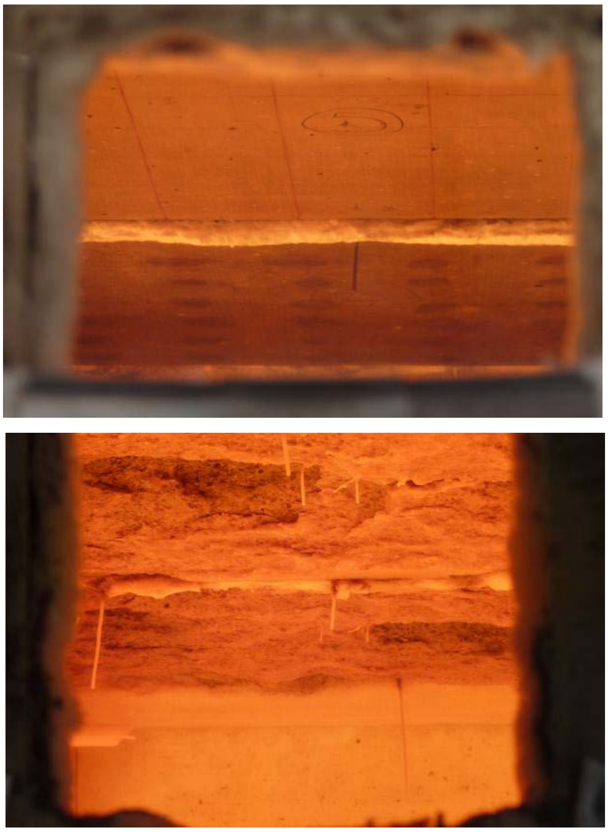

Figure 5: Inside the furnace, view to the bottom side of the specimen at the beginning (top) and during (bottom) the experiment without PP-fibres.

Figure 6 gives an impression on the outside damage of specimens after the experiments. As expected, the surface of the HPC specimen without PP fibers (Figure 6, bottom) is much higher degraded than the one including PP fibers (Figure 6, top).

Figure 6: Specimen with 1 kg PP fibers per m^3 concrete after the experiment (top), specimen without PP fibers showing damage due to spalling (bottom).

Acoustic emission measurements proved these observations. A comparison of the acoustic emission activity of the specimen with and the one without PP fibers is given in Figure 7.

The AE activity is an equivalent for the number of recorded AE signals. During the experiments without PP fibers, the system recorded ten times more events in the same time as in experiments with PP fibers. The AE events recorded during the experiments with PP fibers are mainly due to internal cracking and not spalling. A first comparison between

AE signals due to spalling and signals due to cracking was successful, but needs more investigations.

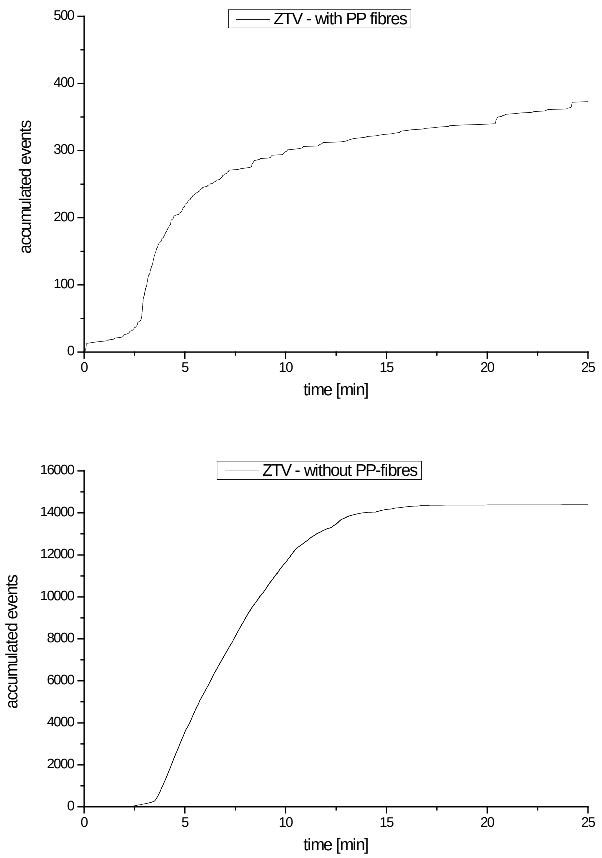

Figure 7: AE activity of experiments for concrete specimens with (top) and without (bottom) PP fibers.

Additional to the acoustic emission measurement a system for continuous ultrasonic velocity measurement was installed (Figure 2 on the middle specimen and Figure 8). It was used to investigate the changing of the ultrasonic p-wave velocity because of temperature exposure.

Figure 8: Coupling of Ultrasonic emitter and receiver.

The results of the ultrasonic measurements are shown in Figure 9 and Figure 10. The graph shows that the velocity is going down by half in the first five minutes of the experiment.

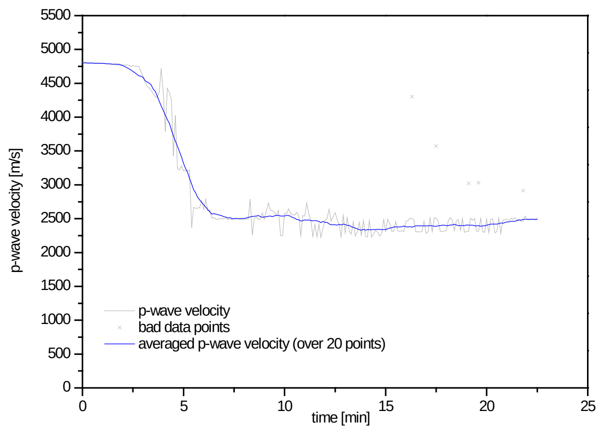

Figure 9: Changing of the HPC P-wave velocity over the time. Specimens without PP-fibres.

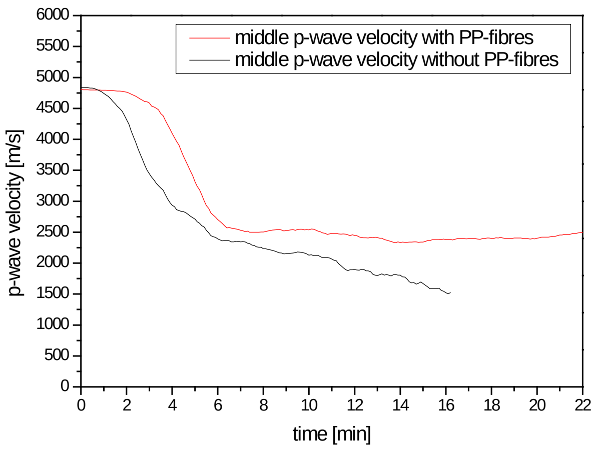

Figure 10: Averaged p-wave velocity of experiments with and without PP-fibres.

A comparison between the ultrasonic measurement results and the acoustic emission activity, which are both an indication of damage of the concrete structure, shows a good agreement (Figure 11).

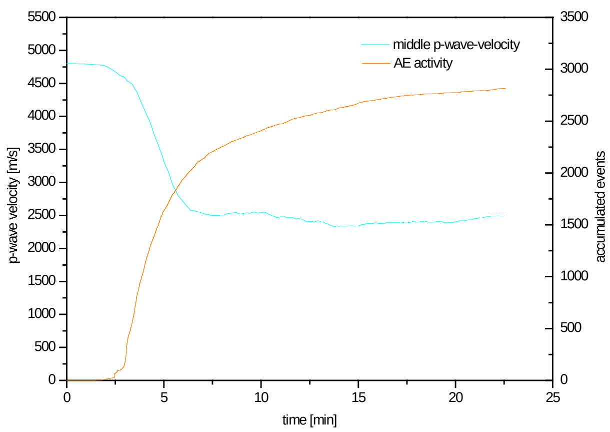

Figure 11: Comparison between the ultrasonic measurement results and the acoustic emission activity.

An example for typical AE signals showing an AE event recorded with eight channels is presented in Figure 12. The vertical lines assign the signal's onset at each channel. With the information of these arrival times it is possible to calculate the source of the signal or the position of spalling processes, respectively.

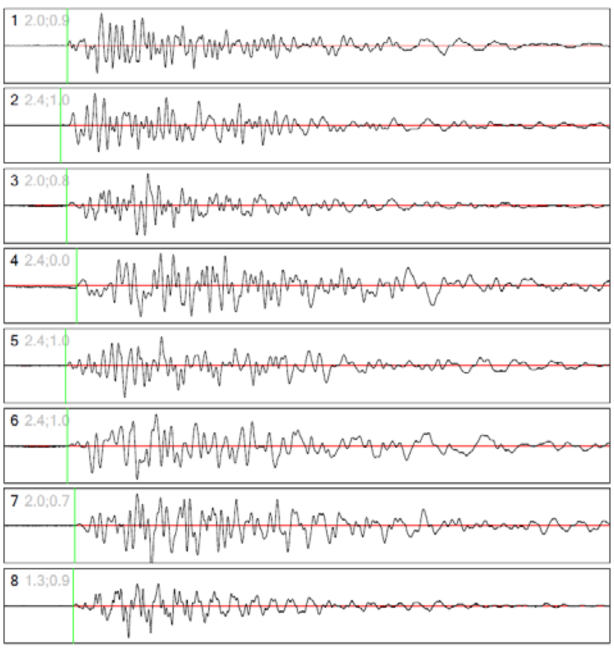

Figure 12: Acoustic emission event recorded by an eight-channel transient recorder.

An example for the localized events of one of the specimens without PP fibres is given in Figure 13 showing a time slot between minute 5 and 10 after the burner was started. The recorded AE signals were classified in a way that only events recorded by six or more sensors are considered and the localization accuracy was better than 15 cm. Most source locations are determined in the centre of the specimen perpendicular to the y-axis. The accuracy of the AE locations given by the deviations in x and z direction is shown in Figure 14. The deviations are smaller in the middle of the specimen compared to the edges which can be explained by the distribution of the sensors [3] (less number of sensors at the edges) and by the temperature gradient inside the specimen that leads to uncertainties of wave velocities. Wave velocities (particularly of compressional waves) have to be known prior to localisation analysis using the current algorithms.

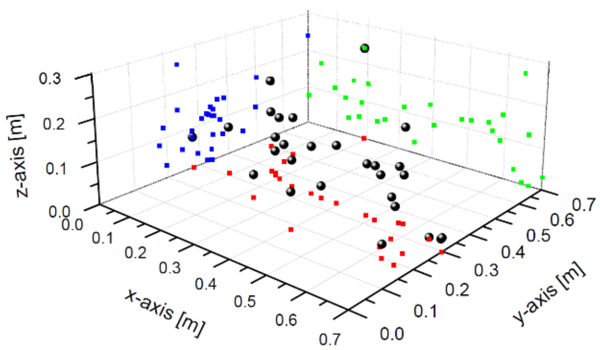

Figure 13: Acoustic emission event recorded by an eight-channel transient recorder.

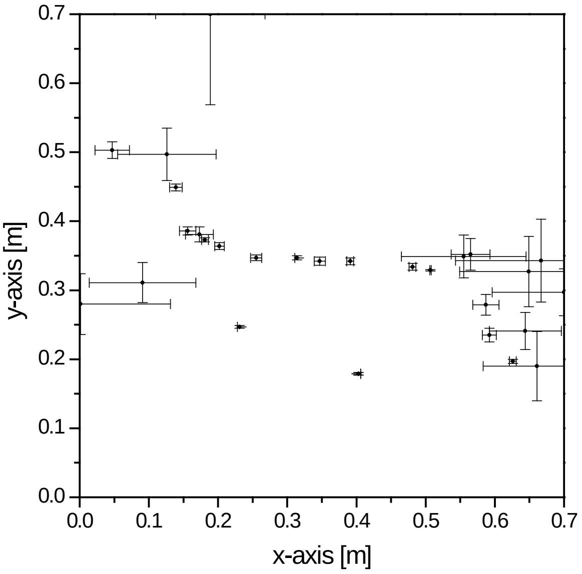

Figure 14: Projection to the x/z plane and error bars of localisation.

4 NUMERICAL ANALYSIS

Thermo-hygro-mechanical model for concrete [6, 8] was recently employed in several studies of explosive spalling of concrete. It was concluded that the main reason for explosive spalling is high pore pressure in combination with thermally induced stresses and thermal degradation of mechanical properties of concrete.

In the framework of the present experimental studies the model was used to reproduce experimental investigations of spalling of HPC. As discussed, in the experiments the explosive spalling is obtained only for concrete without addition of polypropylene.

In the framework of the numerical investigations [1] a number of parametric numerical studies related to explosive spalling were carried out. Numerical results confirm that HPC without polypropylene exhibits explosive spalling. Here are discussed only results related to the influence of different kind of inhomogenities on explosive spalling. It is important to note that explosive spalling of concrete is a local phenomena and therefore local material, geometrical and loading (heating) properties, i.e. their variation in space, must be relevant. For instance, due to the high inhomogeneity of concrete, its porosity can locally be quite different than its average value. Consequently, saturation, permeability and pore pressure at high temperature can locally vary for an order of magnitude, or even more. The large scatter of measured experimental results related to the explosive spalling is most probably due to the fact that the local properties control the problem. Because of these arguments it is important to investigate the influence of local variation of relevant parameters (material properties, loading and geometry) on the explosive spalling of concrete.

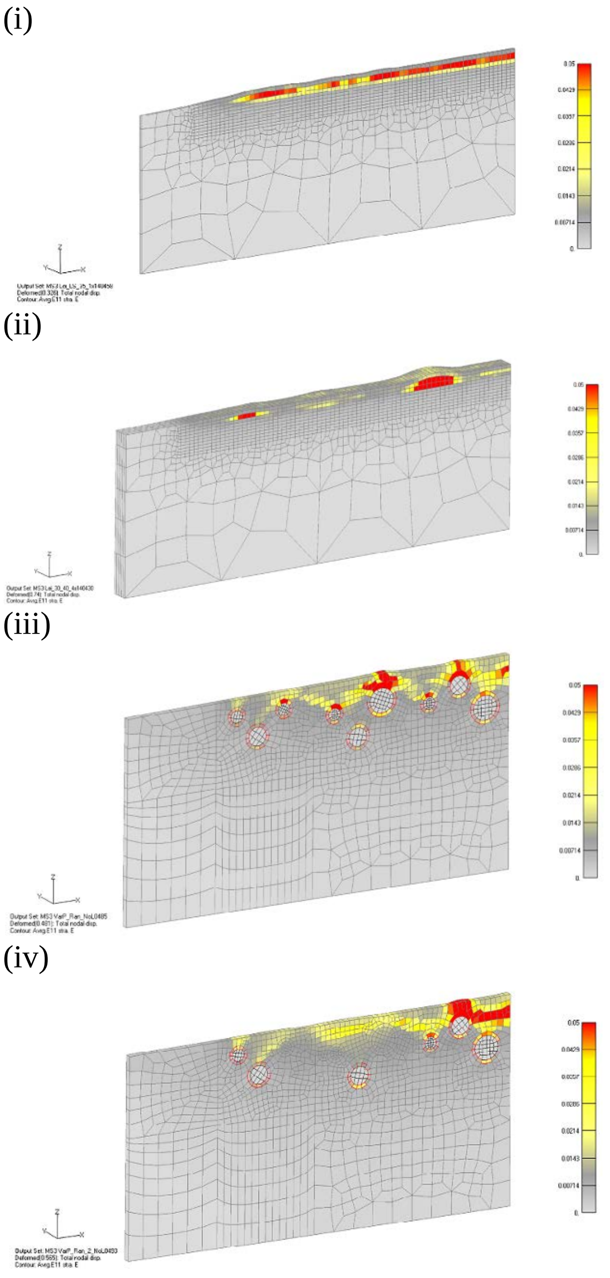

Figure 15: Spalling failure modes in terms of maximal principal strain

Here are elaborated results of the following cases: (i) homogeneity of the material and heating field; (ii) homogeneity of the material and inhomogeneity of heating field; (iii) inhomogeneity of the material which is modeled in discrete sense, i.e. discretized are cement paste (mortar), aggregate peaces and interface. Heating field at the surface of the specimen is assumed to be uniform; (iv) The same as (iii) accept with different distribution of aggregate pieces. In cases (i),(iii) and (iv) only one row 3D solid finite elements are used assuming plane strain condition. In case (ii) four rows of 3D solid finite elements are used assuming plain strain condition, however, the surface of the specimen is not uniformly heated. In cases (iii) and (iv) mechanical properties of mortar and interface are the same as given for macroscopic concrete properties except that the tensile strength of interface is reduced to 0.5 MPa. The aggregate is assumed to be linear elastic. Thermal properties of all components are similar to macroscopic concrete properties except permeability of aggregate pieces which is assumed 100 times smaller than that of mortar. In the contrary to (i) and (ii) in cases (iii) and (iv) stress induced thermal strains are not considered.

Figure 15 shows spalling failure modes in terms of maximal principal strains. In case (i) splitting crack localizes over the entire heated surface of the specimen, what is not realistic. In case (ii) the explosive spalling localizes only on the domain of the surface with slightly higher surface heating. In cases (iii) and (iv) spalling initiates on the aggregate-mortar interface. Obviously, the results indicate strong influence of local conditions on explosive spalling.

5 CONCLUSIONS AND OUTLOOK

The presented results show that AE methods can successfully be used to investigate the phenomena of concrete spalling under fire exposure. It is important to use signal-based acoustic emission techniques to get detailed information. A three dimensional localisation is in the first minutes possible but very difficult because of the changing p-wave velocity related to the large temperature gradient and the micro-cracking phenomena.

In the research project these problems will further be handled. The intention is to include the temporal difference of the acoustic velocity in the calculation of the localisation. The next experiments will also include different parameters like concrete mixtures and observations of other influences like humidity or compressive stress.

By the use of comparison between the acoustic emission measurement and the numerical simulation it is possible to calibrate the model and to get more information about the material behaviour without the requirement of expensive experiments.

Based on the results of numerical investigations the following can be concluded: Explosive spalling of concrete is a local phenomena and therefore the variation of local material, geometrical and loading (heating) properties must have significant effect on the explosive spalling. In reality it is possible that pore the permeability of concrete locally varies by one or even two order of magnitudes. Consequently, the average properties cannot govern explosive spalling. The effects of inhomogeneity should be in future investigated in more detail.

6 ACKNOWLEDGEMENTS

The authors are grateful for the collaboration with MFPA Leipzig GmbH and with Materialprüfungsanstalt Universität Stuttgart (MPA). Thanks for their support are given also to the members of the Center for Building Materials (cbm) and MPA-Bau, both Technical University of Munich (Germany). The research project started January 2010 and is sponsored by the Deutsche Forschungs-gemeinschaft DFG via grant GR1664/7-1.

REFERENCES

[1] J. Ožbolt, J. Bošnjak, G. Periškić and C. Grosse, "Numerical simulation of concrete exposed to high temperature – damage and explosive spalling", *Rilem Proc. PRO80 (Eds. E. Koenders, F. Dehn)*. Proc. 2nd International

Workshop on Concrete Spalling due to Fire Exposure, Delft, 25-32 (2011).

[2] C. Grosse, R. Richter, J. Ožbolt, F. Dehn, M. Juknat, "Spalling of HPC evaluated by acoustic emission and numerical analysis", *Rilem Proc. PRO80 (Eds. E. Koenders, F. Dehn).* Proc. 2nd International Workshop on Concrete Spalling due to Fire Exposure, Delft, 157-163 (2011).

[3] Grosse C., Ohtsu M. (Eds.): Acoustic Emission Testing in Engineering – Basics and Applications. ISBN: 978-3-540-69895-1, 415 p., Springer publ., Heidelberg (2008).

[4] Grosse C., Reinhardt H.-W., Finck F.: Signal-based acoustic emission techniques in civil engineering. J. of Mat. in Civ. Eng. 15 (2003), No. 3, 274-279.

[5] Richter R: Einsatz der Schallemissionsanalyse zur Detektion des Riss- und Abplatzungs-verhaltens von Beton unter Brandeinwirkung. Diplomarbeit, Materialprüfungsanstalt Universität Stuttgart (2009).

[6] Ožbolt J., Kožar I., Eligehausen R., Periškić G.: Instationäres 3D Thermo-mechanisches Modell für Beton. Beton- und Stahlbetonbau, 100 (2005), Heft 1, 39-51. (2005).

[7] Ožbolt J., Reinhardt H.W.: Three-dimensional finite element model for creep-cracking interaction of concrete. Proceedings of the sixth international conference CONCREEP-6 , Ed. By Ulm, Bažant & Wittmann, 221-228. (2001).

[8] Ožbolt, J., Periškić, G., Reinhardt, H.-W. and Eligehausen, R.: Numerical analysis of spalling of concrete cover at high temperature, Computers and Concrete, **5**(4) (2008), 279-293.