

Examination of Reinforced Concrete Beams with Self-Healing Properties by Acoustic Emission Analysis

Fabian MALM *, Christian U. GROSSE *

* Technische Universität München Centrum Baustoffe und Materialprüfung
(cbm), Baumbachstraße 7, 81547 München, Germany

Abstract. Formation of cracks in concrete and its expansion can lead to an increased moisture transport and thus to corrosion processes which can permanently damage the structures. To be able to counteract these impacts, concrete with self-healing properties is going to be developed. There have been different approaches by several research groups and first results have been published [1]. In this study, embedded encapsulated healing agents with two component polymers in reinforced concrete beams have been applied for autonomous crack healing. The interaction between crack formation and capsule breakage is an essential factor for the efficiency of crack repair. Therefore crack-controlled three-point bending experiments, monitored by acoustic emission techniques, have been conducted. Recorded acoustic emissions by a 16-channel transient recorder and piezo-electric broadband transducers led to a localization of these events which should give an indication of the crack formation before and after healing. Results show that the evolution of acoustic emissions correlate with crack formation. Comparisons with the force-time curve confirm these results. Furthermore, a localization of high energy hits is associated with capsule breakages.

1. Introduction

The sustainability and durability of structures in civil engineering is becoming a more and more important issue. In this context self-healing materials for cementitious materials are developed to prolong the lifetime. Different healing mechanisms are already tested and should continue to be evaluated. Promising results have been published by several researchers before [1-8] but still optimisation requirements remain. Developing healing techniques for cementitious materials the self-healing efficiency should be evaluated to observe the usually time and space dependent healing effect. Up to now, the self-healing efficiency has mostly been evaluated based on the amount of regain in mechanical properties after a certain period. While some researchers evaluate the regain in compressive strength, most evaluate the regain in strength, stiffness and/or energy when performing a tensile or bending test. Regain in mechanical properties is then determined by reloading the previously loaded and thus damaged sample and by comparing the mechanical properties gained during reloading at a certain time, with the original properties.

Non-destructive testing methods have – compared to this – obvious advantages [9]. Granger et al. [8] derived the amount of regain in energy due to autogenous crack healing

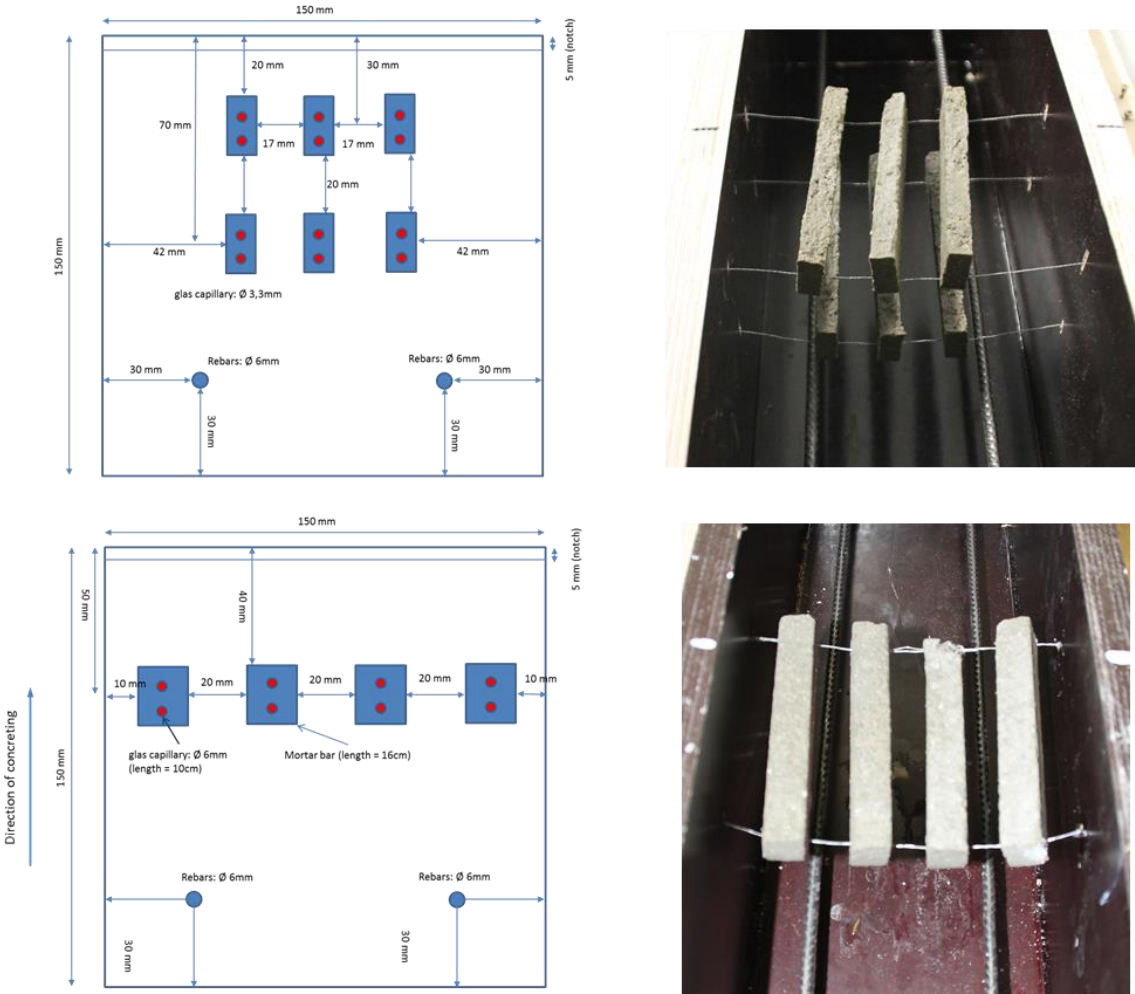


from acoustic emission measurements. In the frame of the Healcon project sponsored by the European Commission the healing efficiency of encapsulated healing agents - embedded in reinforced concrete -, activated due to crack formation, is also investigated by acoustic emission (AE) analysis (and by other NDE techniques). Recorded acoustic emissions as a result of bending load are localized and selected by energy to obtain detailed information of the fracture process [10].

2. Preparation of test specimens

For autonomous crack repair a commercial polyurethane based healing agent (MEYCO MP 355 1K, BASF - The Chemical Company) was used. The prepolymer of polyurethane which is developed for injections to stop flowing water in cracks by becoming foam was filled into glass capillaries with a length of 100 mm and an inner diameter of approximately 2.5 mm and 4 mm, respectively. To shorten the reaction time additional capillaries with a mixture of accelerator and water were added. After filling the tubes with a needle the ends were sealed with HBM X60 (Methyl-Methacrylat).

To protect the fragile glass capsules against the concreting process, they were embedded inside mortar bars. Each mortar part contained two adjacent compounds; one capsule with polymer and one with accelerator and water.



Pic. 1: Setup of the positioning of healing agents in wooden moulds of concrete specimens. Top: 2x6 capillaries with an inner diameter of 2.5 mm (Type 1). Bottom: 2x4 capillaries with an inner diameter of 4 mm (Type 2).

For the concrete test specimens a standard mixture according to DIN EN 206-01 was made. After 28 days the cube compressive strength amounted to 64.0 (± 1.8) MPa. Wooden molds with a dimension of 550 x 150 x 150 mm - based on the EN 12390-5 - were prepared for specimens with and without healing agents. The mortar prisms were fixed by means of thin steel wires into the appropriate position. In order to conduct fairly reproducible and controlled test runs reinforcement bars with a diameter of 6.0 mm were used pairwise. Pic. 1 shows the different positioning setups.

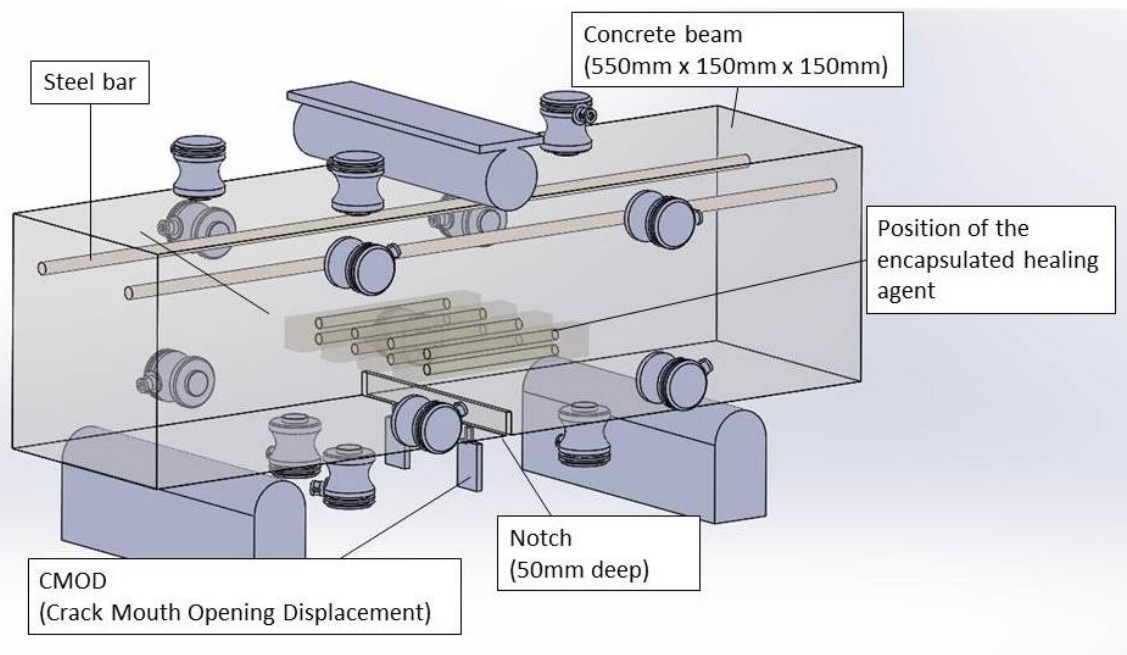
3. Experimental setup

To create 300-350 μm wide remaining cracks in the middle section, samples were loaded in crack-width-controlled 3-point bending tests with a speed of 0.06 mm/min for 10 min. In consequence, capsules break and the healing agent can flow and polymerize. After 7 days of hardening at 20°C and 65% RH, specimens were reloaded using the same setup. In total, 8 samples with and without healing agents were conducted and monitored by acoustic emission analysis.

4. Methods of Acoustic Emission measurements

Acoustic emission (AE) analysis techniques were applied during the 3-point bending tests to provide information about the crack behaviour together with embedded encapsulated healing agents. Up to 15 piezoelectric contact transducers (Panametrics V103) were coupled with hot glue onto the concrete beam in a range of the expected crack zone. Additionally the external force was recorded by the 16-channel transient recorder.

A calibration of the sensitivity of all sensors was applied by the Hsu-Nielsen method. For the calibration of the localization accuracy ultrasonic bursts on the surface were applied in a grid. Teflon strips between the supports and the specimens avoided contact noise during the 3P-bending test.



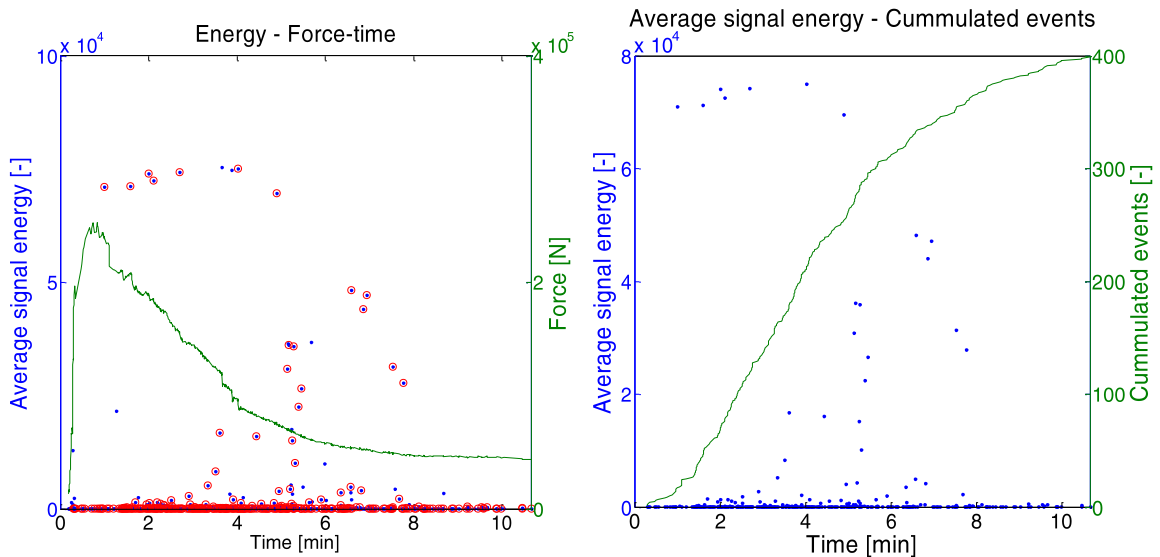
Pic. 2: Setup for a 3P bending test - Positioning of acoustic emission sensors on a reinforced concrete specimen with embedded healing agents.

The behaviour of crack formation has been investigated continuously during loading and unloading of the samples before and after healing. To get reliable automatic onset times the Akaike Information Criterion (AIC) and a threshold picker were used for determination [11]. Finally, events were localized in a three dimensional way with two different methods – Geiger’s method [12] and Bancroft’s method [13]. In the case of Bancroft’s method, to benefit from all the possibilities of a 4-sensor combination a permutation with 15 sensors is computed - for each event. To obtain the most confident localization vector the median coordinate of each axial direction is calculated. Finally the mean of a predefined window on this distribution returns the definite hypocentre coordinates of each event. As a verification of the position of recorded emissions within the samples is not possible, onset times were compared with theoretical travel times from the determined hypocentre to the sensors by means of a correlation coefficient. Based on this approach an optimal detection of a crack formation is investigated. Also a classification of AE events based on their energy is to assign AE events with the highest energy to capsule breakages.

This purpose will now be exemplified on a particular test specimen of Type 2 (Pic. 1).

5. Results

The average signal energy of all recorded and locatable acoustic emissions (blue points: 770 events within the specimen) during a 3P-bending test with respect to time is shown in Pic. 3, left. Red marked blue points indicate localizations (399 events) with a correlation coefficient greater than or equal to 0.8. When reaching the maximum load (Pic. 3, left, green curve) events with strikingly increased averaged signal energy occur. The accumulation of all events (Pic. 3, right) follows an approximately linear progress. To track the crack propagation different time frames were considered (Pic. 4). It is shown that with increasing time events start propagating from the notch to the centre and finally to the position of the reinforcement bars.



Pic. 3: Left: Average signal energy of all recorded and locatable events (within the specimen) during a 3P-bending test. Red marked events feature a correlation coefficient of 0.8. Additionally the force-time curve.
Right: Correlation between average signal energy of single events and progress of accumulation over time.

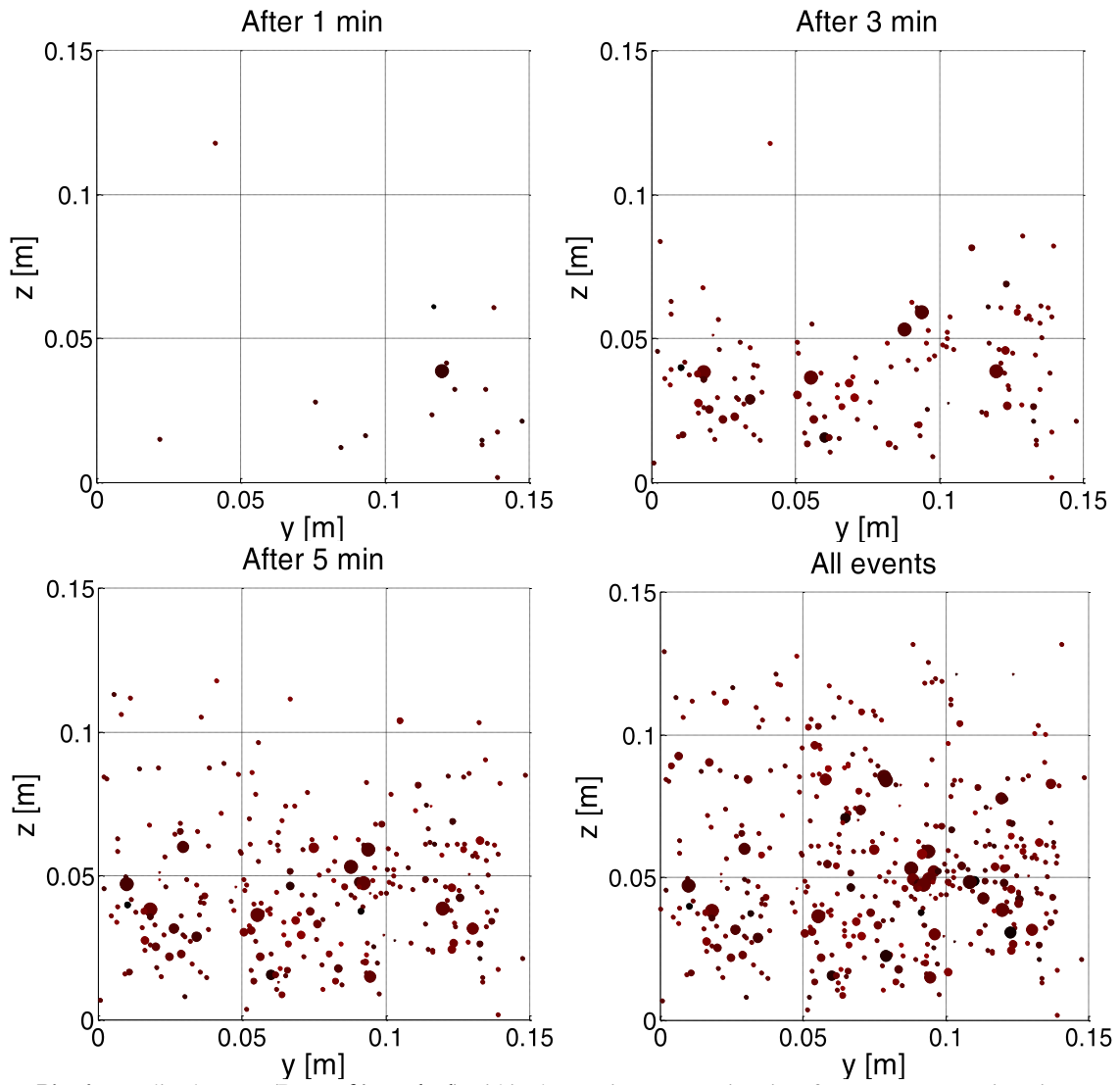


Fig. 4: Localized events (Bancroft's method) within the specimen at varying time frames – cross-section view.

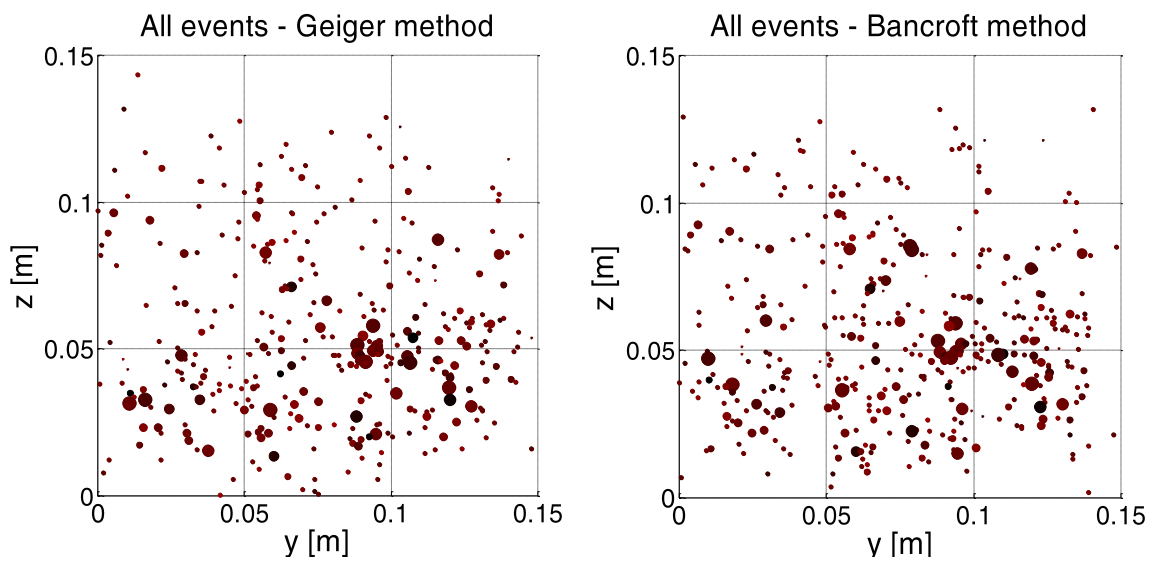
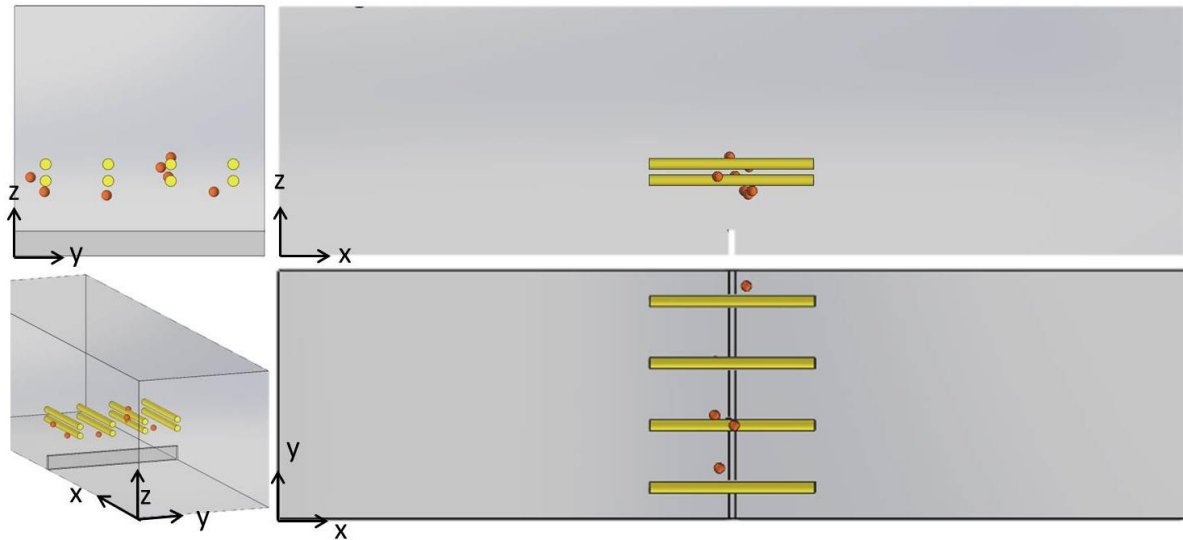


Fig. 5: Comparison of localized events of Geiger- (347 events) and Bancroft- (399 events) method with a correlation coefficient of 0.8.

Pic. 5 shows a comparison of localized event positions between the algorithms of Bancroft and Geiger considering the effect of the correlation coefficient. Apart from this interaction the interpolation method of Geiger reveals less results. To identify acoustic emissions which are related to breakages of the embedded glass capillaries, events were selected by energy. As seen in Pic. 3, left, signals with an average energy greater than $6 \cdot 10^4$ [-] occur directly after the maximum value of load. A localization of these emissions indicates a strong correlation between capsule breakages and high-energy signals (Pic. 6).



Pic. 6: Localized events (Bancroft method) with an averaged signal energy over $6 \cdot 10^4$ [-].

6. Conclusion

In this study, the application of acoustic emission analysis was verified for monitoring the crack formation and the self-healing efficiency with regard to glass capillaries. It has been demonstrated that signals with high energies could be located close to the position of embedded capsules and thus correlates to capsule breakages. A significant contribution was done by the approach of permutation of all sensor combinations which enhances the localization accuracy. Nevertheless, solely a preselected number of events were useable for localization. Besides material properties of concrete (e.g. inhomogeneity, air and water content) metrological influences like overdrive of signals and weak SNR limit the characterisation of material changes during loading.

Acknowledgements

We thank all involved colleagues of the Centre for Building Materials and also all students for support and assistance. Special thanks go to our technician Marina Nahm.

The research as described in this paper has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 309451 (HEALCON).

References

- [1] Van Tittelboom, K.; De Belie, N. (2013) Self-Healing in Cementitious Materials—A Review. *Materials* 2013, 6, 2182-2217

- [2] Edvardsen, C. (1999). Water permeability and autogenous healing of cracks in concrete. *ACI Materials Journal*. 96(3):448-455.
- [3] Yang, Y, Lepech, M.D., Yang, E.-H., Li, V.C. (2009). Autogenous healing of engineered cementitious composites under wet–dry cycles. *Cement and Concrete Research* 39. 382–390
- [4] Jonkers, H.M. (2011) Bacteria-based self-healing concrete. *Heron* 56 (1/2), pp 1-12.
- [5] Van Tittelboom K, De Belie N, Van Loo D, Jacobs P (2011) Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent. *Cement and Concrete Composites* 33 (4), pp 497-505.
- [6] Van Tittelboom K, De Belie N (2010a). Self-healing concrete: suitability of different healing agents. *International Journal of 3R's* 1 (1), pp 12-21.
- [7] Granger S, Loukili A, Pijaudier-Cabot G, Chanvillard G (2007). Experimental characterization of the self-healing of cracks in an ultra-high performance cementitious material: Mechanical tests and acoustic emission analysis. *Cement and Concrete Research* 37 (4), pp 519-527.
- [8] Tsangouri, E, et al. (2013). Detecting the Activation of a Self-Healing Mechanism in Concrete by Acoustic Emission and Digital Image Correlation. *The ScientificWorld Journal*. Volume 2013, Article ID 424560, 10 pages.
- [9] Grosse, C.U., Van Tittelboom, K., De Belie, N. (2013). Non-destructive testing techniques for the observation of healing effects in cementitious materials – an introduction. *Proc. 4th International Conference on Self-Healing Materials – ICSHM*. Ghent.6 p.
- [10] Grosse, C.U., Ohtsu M. (2008). *Acoustic Emission Testing in Engineering - Basics and Applications*. Springer publ., Heidelberg, ISBN: 978-3-540-69895-1, 404 p.
- [11] Raith, M. (2013). Schallemissionsanalyse bei Pulloutexperimenten an Verbunddübeln. Master's Thesis. Lehrstuhl für Zerstörungsfreie Prüfung. Technische Universität München
- [12] Geiger, L. (1910). Herdbestimmung bei Erdbeben aus den Ankunftszeiten. *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse* 1910, S. 331–349.
- [13] Bancroft, S. (1985). An Algebraic Solution of the GPS Equations. *Aerospace and Electronic Systems, IEEE Transactions on AES-21*(1): 56-59.