2nd International RILEM/COST Conference on Early Age Cracking and Serviceability in Cement-based Materials and Structures - EAC2
12–14 September 2017, ULB-VUB, Brussels, Belgium

Concrete Fracture Energy Increase by Embedding Capsules with Healing Ability: The Effect of Capsules Nature

Eleni Tsangouri*[a], Francisco A. Gilabert[b], Dimitrios G. Aggelis[a], Nele De Belie[c], Danny Van Hemelrijck[a]
[a] Dept. Mechanics of Materials and Constructions (MeMC), Vrije Universiteit Brussel (VUB), Brussels, Belgium
[b] Dept. Materials, Textiles and Chemical Engineering, Ghent University, Ghent, Belgium
[c] Magnel Laboratory for Concrete Research, Dept. Structural Engineering, Ghent University, Ghent, Belgium

ABSTRACT

Concrete is the basic material of infrastructures since it is cost-effective, efficiently produced and strong. Despite its popularity, under service-loads the concrete matrix suffers from flaws that can be crucial for its durability. To overcome the shortcoming in durability, concrete is traditionally reinforced by steel or its mixture is modified by introducing additives that enrich the autogenous crack closure. Nowadays, an alternative solution is proposed namely autonomous healing. Repair polymer agent is encapsulated into tubes and embedded into concrete during mixture. The tubes break as soon as a crack wider than 100 μm is propagated across them. Only at this moment, the agent is released and polymerized. The crack void is sealed and repaired (mechanical features restored as well). The previous years, researchers at the Dept. Mechanics of Materials and Constructions, VUB have studied the mechanical performance of newly developed healing systems and evaluated their repair efficiency. In this study, an additional benefit of autonomous healing is assessed: the short or long tubes contribute as local reinforcement of concrete under tensile load and enhance the fracture toughness. The energy release rate and other fracture mechanics parameters are measured for plain concrete beams tested under three-point bending. The reference case (concrete carrying no healing system) is compared to cases at which different encapsulation systems are applied. Additionally, the study of fracture is correlated to the findings of inspection with different non-destructive techniques. The effect of tubes design (geometry, shape, material) on the fracture toughness is studied leading to the most promising healing system.

Keywords: Concrete, self-healing, encapsulated healing agent, fracture energy, toughness

1. INTRODUCTION

1.1. Damage and healing on concrete

The concrete performance under loading is characterized by the material strength in healthy state and the fracture toughness as soon as cracking occurs. Due to the wide range of components size and mainly due to aggregates presence, concrete breaks in a quasi-brittle manner: flaws or defects create micro-cracks that progressively join to form macro-cracks. This means that concrete develops a widely spread damage zone around the crack that may not be negligible. The latter, named fracture process zone (FPZ), can be up to 100mm wide around the crack at the ultimate load and has the ability to transfer stresses from the crack to the fracture vicinity [1]. In practice, the strain formed due to cracking is entrapped into the FPZ and the rest of the sample remains stress-free. The microcracking formed into the FPZ concentrates the tensile stresses and leads to crack branching due to aggregate interlocking [2].
The FPZ, schematically presented in Figure 1, dominates the crack nucleation and propagation and introduces the strain-softening (stress progressively decreases as the crack widens) phenomena that characterize the post-peak concrete response under mode-I failure.
Autonomous healing, by means of encapsulating polymer-based healing agent into concrete during casting, aims to improve the concrete durability and control the crack growth phenomena which might lead to catastrophic failure. In principle, the healing mechanism introduces a crack closure process and arrests the fracture progress of concrete. The fracture mechanics theories and models are applied to decompose the multi-scale and complex cracking phenomena, therefore they play a key role in the study of autonomous healing.

*eleni.tsangouri@vub.be; phone 0032 2629 2928

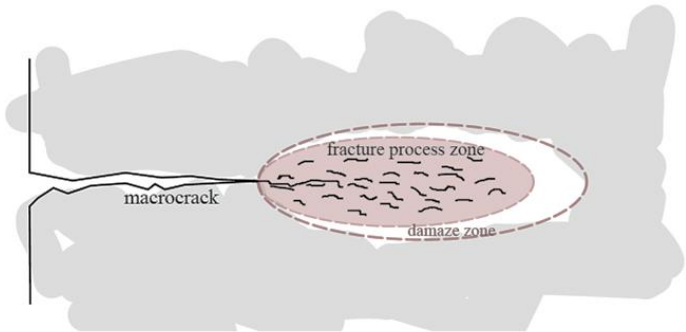


Figure 1: The Fracture Process Zone (FPZ) as a crack propagates in concrete.

1.2. Fracture constitutive law

The concrete resistance to crack propagation, namely toughness, and the ability to mechanically reset after healing should be examined considering the energy released due to fracture. Several constitutive models are developed exploring toughness. Among them (cohesive crack models of Barenblatt-Dugdale [3], crack-band model of Bazant-Peterson [4]), the well-established fictitious model introduced by Hillerborg is recommended by the Rilem organization (Rilem TC 50-FMC committee) [5-6]. In Figure 2, based on the fictitious model, the loading response of pre-cracked unreinforced concrete under mode-I crack opening is presented by means of two curves, an initial linear stress-strain (σ-ε) curve (uncracked stage) and the subsequent stress-crack opening (σ-crack opening displacement (cod)) curve formed after cracking.

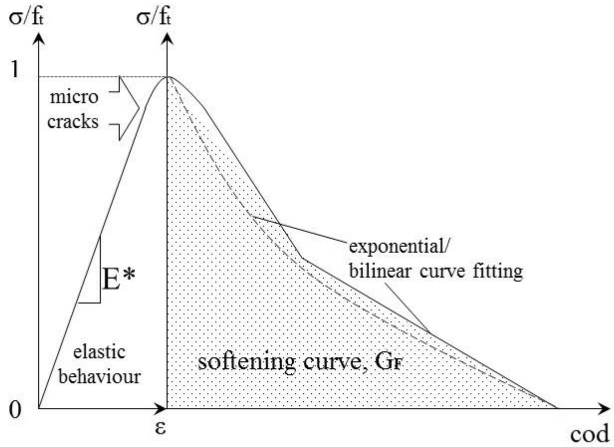


Figure 2: The fictitious model of concrete fracture.

The stress-strain response becomes non-linear as the concrete's tensile strength (ft) is reached. At this stage microcracks develop near the pre-crack. Those microcracks evolve without giving rise to significant deformation on concrete and thus the fracture energy dissipated is limited [2, 7].

At the peak of stress, a unique macrocrack forms and propagates. The crack discontinuity changes the measurement value from strain (ε in %) to crack opening displacement (cod in mm) as shown at the horizontal axis in Figure 2. As the crack opens the stresses on concrete gradually decrease (strain softening). The softening phenomena appear due to local FPZ development. The absorbed energy called fracture energy (G_F in N/m), is equal to the area under the stress(σ)-crack opening (cod) envelope and is considerably bigger than the initial microcracking fracture energy.

The measurement of fracture energy absorbed on both concrete fracture phases is the key tool to evaluate the original resistance of material to damage and the reset of material toughness after healing. In the following paragraphs, concrete samples are prepared and tested according to the evaluation method presented in Rilem TC 50-FMC fracture toughness protocol [6]. At first, reference concrete samples without healing are studied in order to characterize the original fracture response of concrete.

2. MATERIALS AND METHODS

2.1 Concrete composition

Plain concrete samples are cast into wooden moulds and consequently vibrated. The absence of reinforcement guarantees pure crack opening phenomena under bending. Normal strength concrete with water/cement/sand ratio of 1/2.07/4.28 is chosen. The maximum aggregate size is 13 mm. One day after casting the hardened concrete samples are removed from the mould and placed in water for 13 days. The samples are tested under three-point bending the 14th day after casting (until concrete strength is sufficiently gained).

2.2 Healing concept

Two component (polymer and water-based catalyst) polyurethane agent is encapsulated into a pair of hollow tubes. The tubes are filled with the agent, sealed, attached in pairs and placed at the zone that suffers from tension under service loads. This study does not consider the agent healing performance previously discussed in other studies [8]. The tubes are manufactured by glass or cement.

Thin and thick glass tubes break but also suffer from debonding effects at the concrete-glass interphase. To overcome this issue, cementitious-based tubes are considered. The cementitious tubes perform better when attached in concrete since the interfacial bonding is great due to materials compatibility (both same cementitious nature). The effect of each capsule system on concrete fracture response will be studied in the following paragraphs.

The tubes have an average internal diameter of 3mm. The thickness varies from 0.175 (thin glass) to 1mm (cement or thick glass). The tubes cannot survive the concrete mixing process (they rupture during mixing), therefore should be attached to the mould before casting. In contact with air and water, the released agent polymerizes in less than 24 hours and expansive foam is developed. The foam has high tensile strength and elastically deforms as the crack reopens. The agent fills the crack void, seals the damaged area and provides mechanical continuum to the structure.

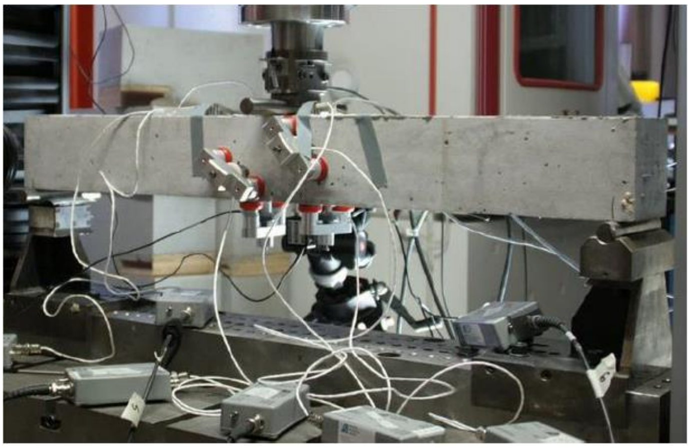


Figure 3: The test setup.

2.3 Test procedure

The sample dimensions are chosen according to the Rilem Technical Committee TC 50-FMC recommendation report. Prismatic beams 840mm long, 100mm wide and 100mm high are prepared and schematically presented in Figure 3. A notch is formed at the bottom of the sample by use of a teflon strip. The notch is created at the middle section and its presence is compulsory in order to induce crack formation at the middle of the beam. The notch covers the width of the beam and its cross-section is 3mm wide and 10mm high.

A Crack Mouth Opening Displacement (CMOD) device is positioned over the notch to provide a precise display of the crack opening. Prior to testing, the CMOD gauge is calibrated on 10.00 mm amplitude. The concrete beam is loaded under deflection control (displacement rate 0.04mm/min) up to crack opening of 0.3mm.

Based on TC 50-FMC protocol, the fracture energy G_F is given by the equation:

$$G_F = \frac{W_O + \mathrm{mg}\delta_o}{A_{lig}}$$

where the symbols stand for:
W_o=area under the load-deflection envelope (Nm)
m= weight of sample (kg)
g= acceleration due to gravity = 9.81m/s^2
δ_o=maximum deflection (mm)
A_{lig}=projection of the fracture zone on a plane perpendicular to the beam axis = 90mm x 100mm.
Furthermore, the areas under the bilinear curve are measured by means of triangles covering the area under the loading envelope (shown in Figure 2). Empirical fracture studies show that the first and the second triangle are equivalent to the energy absorption corresponding to a) crack formation until almost the top of the beam and b) crack widening until final failure respectively [7].

The fracture energy is measured for the following testing series:

- Reference: reference beams in which capsules are not considered;
- Thin glass: beams carrying thin glass capsules;
- Thick glass: beams carrying thick glass capsules;
- Cementitious: beams carrying cement-based capsules.

3. RESULTS

3.1. Mechanical response

In Figure 4, the load-deflection and load-crack opening, stress-strain and stress-crack opening plots derived from reference and healing series are given. It is shown that in all cases, the crack generates at the pre-notched region at the bottom of the beam. Concrete elastically responds until almost the peak of load (pre-peak stage). This part of the test is fully controlled by concrete matrix mechanical response. As the peak load is reached, a unique crack forms and capsules breakage phenomena initiate. The unique crack propagates progressively and in stable mode along the beam's height. The ultimate load is almost the same for all cases, while slightly greater and lower load is obtained in the Thick Glass and Cementitious series respectively (Figure 4a-d).

At the post-peak stage, strain softening phenomenon occurs: stress decreases as the crack widens fitting to a bilinear curve. The transition point indicates the end of crack formation. After that point, the crack only widens. The fitting is well presented in the reference series (see Figure 4a). The phenomenon is less distinct at the healing cases due to capsules contribution to toughness. Actually, the moment a capsule breaks, the load instantly and significantly drops. The latter is verified by Acoustic Emission and Digital Image Correlation analyses done in other studies [8-9]. As a result, the load does not evolve as normal (reference case) but several large changes in its slope, referred to as knees on the loading graphs are detected. The greatest knees are shown in the Thick Glass series, while the phenomenon is almost negligible in the Cementitious case. This can be attributed to the interfacial bonding between the capsules and the matrix: the cementitious capsules develop great adhesion to the concrete matrix since both materials have common nature. In contrast, glass smooth surfaces cannot adhere to concrete and as result easily debond from concrete and respond differently in concrete under loading [10].

3.2. The fracture energy

Based on the fictitious model, the post-peak stage is analysed further: the loading response is represented by bilinear fitting at which the kink point defines the transition from crack propagation and widening to pure crack widening stage. The two parts of this bilinear fitting are schematically presented with triangle shapes covering the area under the stress-cod curve in Figure 5a, b for the Reference and the Thin Glass Capsules series respectively. Only the thin glass capsule case is discussed in this section since is up to date the most popular encapsulation size for self-healing concrete systems.

It is shown that the reference sample response fits well to the bilinear model. On the other hand, at the early stage of the healing case there is a part of the loading graph that cannot fit into the bilinear model and is schematically presented by a box coloured in horizontal stripes. Furthermore, the first part of the bilinear fitting is bigger in size than the second part. This is due to capsules presence that act locally as reinforcement, increase the toughness of the material and therefore enhance the material resistance to crack propagation and widening.

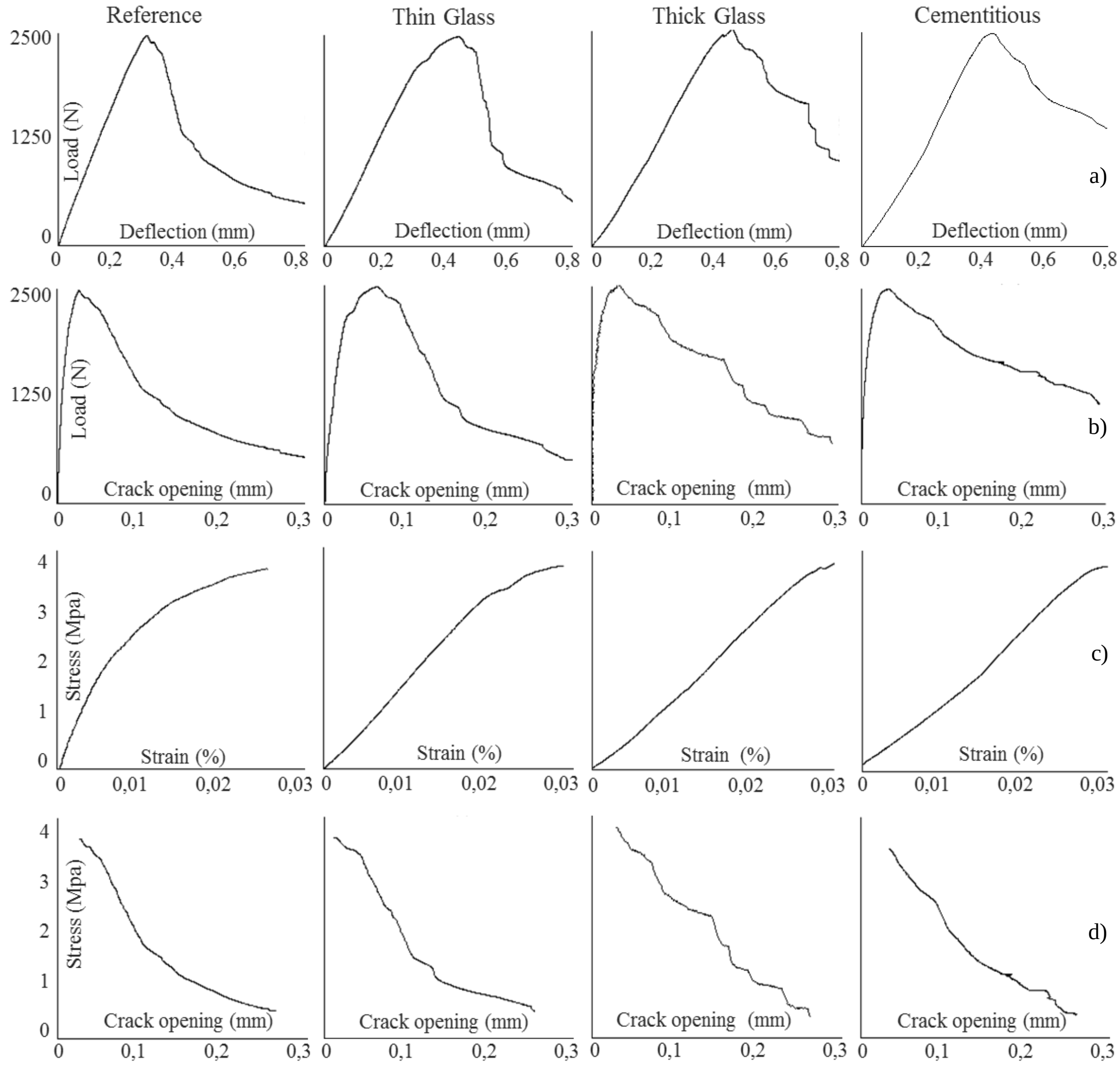
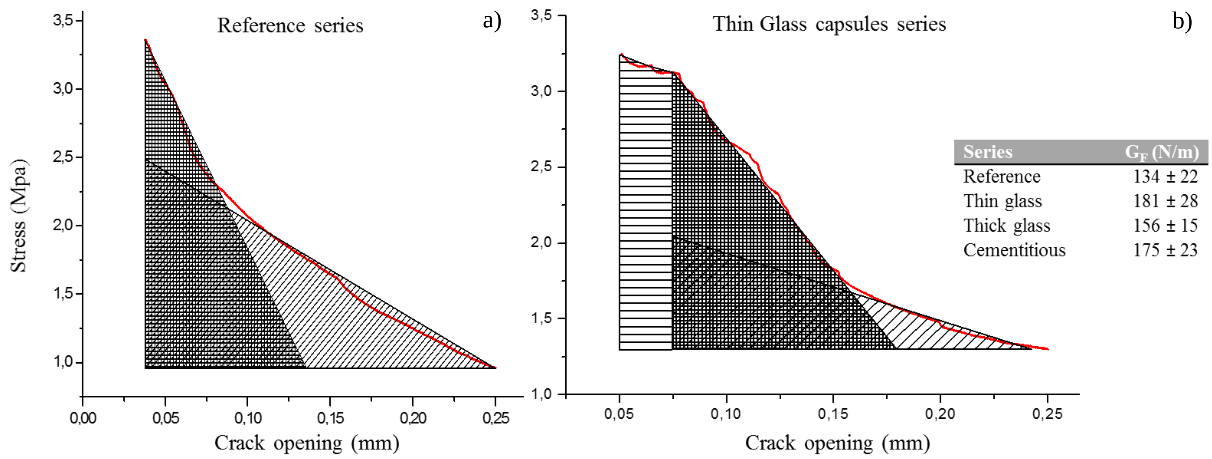


Figure 4: a) Load-deflection; b) Load-crack opening; c) Stress-strain at the pre-peak stage; d) Stress-crack opening at the post-peak stage for the four series of encapsulation systems (reference, thin glass, thick glass and cementitious).



Series	G_F (N/m)
Reference	134 ± 22
Thin glass	181 ± 28
Thick glass	156 ± 15
Cementitious	175 ± 23

Figure 5: The post-peak load-crack opening response of a) Reference and b) Thin Glass capsule series. The bilinear fitting is schematically presented considering two triangles highlighted with stripe lines. The table summarizing the average value of fracture energy (G_F) for all study cases is given as well.

For the sake of completeness, the fracture energy (G_F) measured according to Rilem TC 50-FMC protocol is given by means of average value for all the series in the table in Figure 5. It is observed that the fracture energy increases in the presence of capsules and gets significantly greater values when thin glass or cementitious capsules are used. The latter observation should be investigated further considering the capsule-concrete bonding conditions, the capsule's mechanical features (toughness, brittleness) and the effect of capsule's geometry (thickness, diameter). In parallel to experimental studies, the effect of the aforementioned features on material performance is recently assessed using numerical simulations [11].

4. CONCLUSIONS

The effect of encapsulated healing systems on the fracture toughness of concrete is evaluated considering the bending response of healthy, small-scale and pre-notched concrete beams. Based on Rilem TC 50-FMC protocol, the fracture energy is measured in the reference case (no capsules are embedded into concrete) and in the cases that thin/thick glass and cementitious capsules are used. It is concluded that the capsules act beneficially on the loading response and contribute as local reinforcement on concrete enhancing its resistance to damage. Apparently, the autonomous healing design, not only provides autonomous repair of cracks (by means of healing agent release and sealing of the open cracks), but also improves healthy concrete mechanical response to cracking. Apart from this study, our research considers the application of different non-destructive techniques (Acoustic Emission, Digital Image Correlation, Ultrasound Pulse Velocity, Optical Microscopy) that highlight the contribution of encapsulated healing systems [8-9, 12] and the design of large-scale concrete elements with repetitive self-repair capacity (vascular piping design [13-14]). The outcome of this study aims to provide essential feedback to our research and assist the analysis of complex phenomena in damaged, healed and re-damaged concrete.

REFERENCES

1. Van Mier J. Fracture processes of concrete. Vol. 12. CRC press; 1996.
2. Hu, X., Wittmann, F.H.: Fracture energy and fracture process zone. Materials and Structures. 25 (6), 319-326 (1992)
3. Barenblatt, G. The mathematical theory of equilibrium cracks in brittle fracture. Advances in applied mechanics. 7(1), 55-129 (1962)
4. Bazant, Z., Byung, H.: Crack band theory for fracture of concrete. Materiaux et construction, 16 (3), 155-177 (1983)
5. Modeer, M., Hillerborg, A., Petersson, P.E.: Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and concrete research. 6 (6), 773-781 (1976)
6. Rilem TC-50 FMC, Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. Material Structures, 8 (106), 285-290 (1985)
7. Hillerborg, A. Theoretical basis of a method to determine the fracture energy concrete. Materials and Structures. 18(4), 291-296 (1985)
8. Van Tittelboom, K., Tsangouri, E., Van Hemelrijck, D., De Belie, N.: The efficiency of self-healing concrete using alternative manufacturing procedures and more realistic crack patterns. Cement and concrete composites. 57, 142-152 (2015)
9. Tsangouri, E., Aggelis, D. G., Van Tittelboom, K., De Belie, N., Van Hemelrijck, D.: Detecting the activation of a self-healing mechanism in concrete by acoustic emission and digital image correlation. The Scientific World Journal. 424560, 1–20 (2013)
10. Gilabert, F. A., Van Tittelboom, K., Tsangouri, E., Van Hemelrijck, D., De Belie, N., Van Paepegem, W.: Determination of strength and debonding energy of a glass-concrete interface for encapsulation-based self-healing concrete. Cement and concrete composites. 79, 76-93 (2017)
11. Gilabert, F.A., Garoz, D., Van Paepegem, W.: Macro- and micro-modeling of crack propagation in encapsulation-based self-healing materials: Application of XFEM and cohesive surface techniques. Materials & Design. 130, 459–478 (2017)
12. Tsangouri, E., Karaiskos, G., Aggelis, D. G., Van Hemelrijk, D., & Deraemaeker, A. (2014). Healing performance on concrete under mode I fracture by ultrasonic testing using embedded transducers, acoustic emission and digital image correlation method. In 9th Int. Conf. on Structural Dynamics (EURODYN 2014), Porto, Portugal, June 2014, ISBN 9727521657

13. Van Tittelboom, K., Wang, J., Araújo, M., Snoeck, D., Gruyaert, E., Debbaut B., Derluyn, H., Cnudde, V., Tsangouri, E., Van Hemelrijck, D., De Belie, N.: Comparison of different approaches for self-healing concrete in a large-scale lab test. Construction and Building Materials. 107, 125-137 (2016)
14. Minnebo, P., Thierens, G., De Valck, G., Van Tittelboom, K., De Belie, N., Van Hemelrijck, D., Tsangouri, E., A Novel Design of Autonomously Healed Concrete: Towards a Vascular Healing Network. Materials. 10 (1) 49, 1-23 (2017)