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Structural performance of reinforced concrete beams with self-healing cover zone

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Abstract. In the current study, experiments were carried out to investigate the structural performance of reinforced concrete (RC) beams with a self-healing cover zone. The cover zone consists of a 1.5-cm-thick layer of bacteria-embedded strain hardening cementitious composite (SHCC) for a combination of crack width control and crack healing. The aim is to bring together two emerging technologies (i.e., self-healing and strain-hardening) that show great potential for realizing highly efficient concrete structures. RC beam without the self-healing cover was also prepared as the control specimen for comparison purposes. The experimental program includes loading the beams to failure in four-point bending configuration and sawing the beams to segments for crack pattern analysis and crack healing. Results show that the beams with self-healing cover exhibited a 45-60% improvement in structural capacity. The crack patterns of the hybrid beams were also largely modified. While the reference beam formed only a few major cracks, the hybrid beams formed around 40 fine cracks in the constant bending moment region with an average crack width smaller than 0.2 mm even at maximum load. By having an improved cracking behavior and an enhanced self-healing capacity, it is expected that the beams with a self-healing cover will possess an extended service life at the expense of minimal additional cost.

1 Introduction

Cracking in concrete is an accepted phenomenon and does not have to cause problems if it remains within limits. These limits are laid down in codes describing what are acceptable crack widths for concrete structures in specific environments. Depending on the concrete mix composition, the reinforcement and the cover can thus be designed in such a way that the durability of the structure is secured within its designed service life. This means that for infrastructures with long required service lives or functioning in aggressive environment, a large amount of reinforcement must be designed in the structure such that the probability of having a crack larger than the desired crack width is acceptable, which usually lead to huge economical and environmental burden.

Instead of designing extra reinforcement in excess of what the structural capacity demands, another strategy to 'manage' the risk of crack occurrence is to apply concrete with high crack-sealing capacity: self-healing concrete. Over the last decades, extensive research has been carried out either to stimulate the intrinsic/autogenous self-healing capacity of cementitious materials (i.e., via use of mineral additives [1,2], crystalline admixtures [3]or superabsorbent polymers [4]) or to develop novel autonomous self-healing mechanisms (i.e., via the application of micro-, macro-, or vascular [5] encapsulated polymers, minerals, or bacteria [6]). With a wide variety of test methods assessing the healing efficiency and numerical models simulating the healing mechanisms being developed, researchers have shown conclusively that both mechanical and durability properties can be regained via healing and that autonomous self-healing mechanisms can heal cracks of 300 μm, even sometimes up to more than 1 mm [7,8].

Although at laboratory scale self-healing techniques have been extensively investigated, real site applications of self-healing concrete have been rarely reported. Maintaining a high self-healing efficiency has been considered as the main challenge for this upscaling from laboratory scale toward real-life concrete applications. In the laboratories, tests are usually performed on mortar specimens (without coarse aggregates). When keeping the dosage of the additives (healing agents) constant relative to the cement weight, the move from mortar to concrete (with coarse aggregates) results in a significant dilution of the additives. Alternatively, if the dosage is kept same in proportion to the total volume, a high healing agent content will also result in unacceptable high cost and severe disruptions in workability and mechanical properties of the concrete. Therefore, the approach of simply applying self-healing additives in bulk concrete seems not to be technically and economically viable. Strategic application approach that enables use of self-healing additives only locally, instead of in bulk, is thus needed.

A composite system with a reinforced concrete core and a self-healing cover-zone (as shown in Fig. 1) can

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be one of the promising ways to apply the self-healing techniques in RC concrete elements with the potential to be scaled up for real site applications. By applying self-healing technologies only in the concrete cover-zone, the actual zone which controls the durability of reinforced concrete structures, unnecessary use of self-healing material can be saved and at the same time the detrimental effects of including the additives in bulk concrete can be avoided.

The current study thus aims to investigate the efficiency of such a covered system. Specifically, structural experiments were carried out to investigate the structural performance of reinforced concrete (RC) beams with a self-healing cover zone. The cover zone consists of a 15-mm-thick layer of bacteria-embedded strain hardening cementitious composite (SHCC) [9] for a combination of crack width control and crack healing. In total 2 beams with the self-healing cover were prepared and tested. RC beam without the self-healing cover was also prepared as the control beams for comparison purposes. The experimental program includes loading the beams to failure in four-point bending setup and sawing the beams to segments for crack pattern analysis and crack healing.

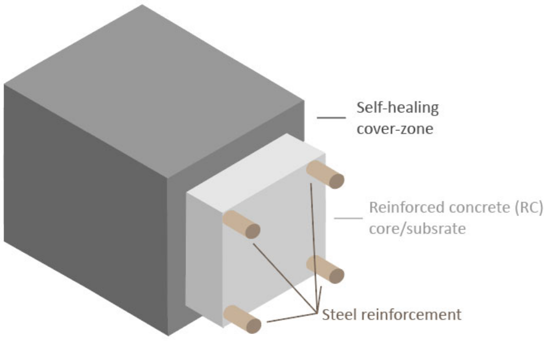


Fig. 1. Schematic illustration of RC beams with the self-healing cover zone.

2 Material and methods

2.1 Experimental design

The test program consists of 3 beams, including 1 conventional reinforced concrete beam as a reference specimen and 2 hybrid beams consisting of a 15-mm-thick U-shape SHCC cover in the front, bottom and back sides of the beams. The geometry and reinforcement details of the beams are given in Fig. 2 and Fig. 3. The 1st hybrid has a smooth interface between the bottom SHCC layer and the reinforced concrete, while the 2nd hybrid beam has a profiled interface which is made of a line of protruding shear-key (SK) from the SHCC layer. Both hybrid beams have a pattern of the keys at the vertical (lateral) interfaces to ensure sufficient mechanical interlocking between the cover and the core and to ensure their deformational compatibility. The pattern consists of equally sized and evenly spaced circular keys which have a diameter of 25 mm and a height of 10 mm. The spacing between the keys is 25 mm, which is designed such that the largest aggregate in the concrete can fill into the gap between 2 adjacent keys.

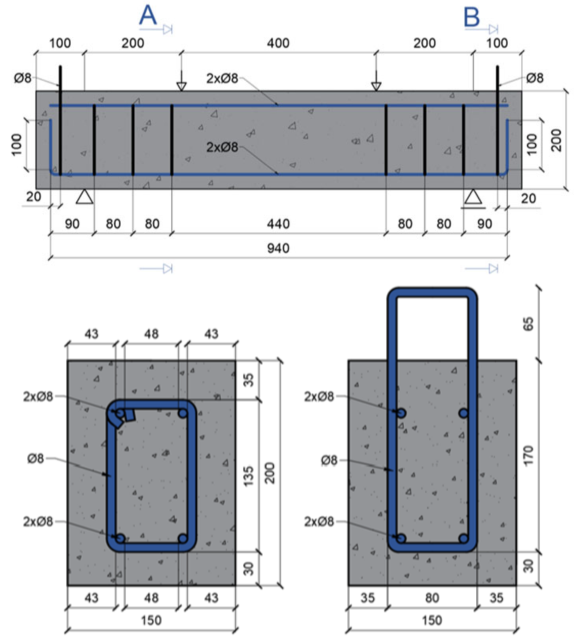


Fig. 2. Design details of the reference beams [unit in mm].

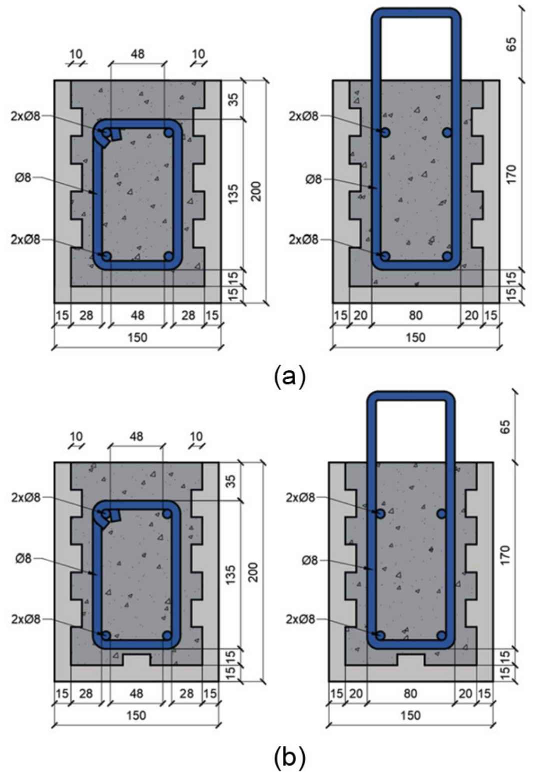


Fig. 3. Design details of the two beams with self-healing cover: (a) beams without bottom shearkey and (b) beams without bottom shearkey [unit in mm].

2.2 Materials and sample preparation

Table 1 and Table 2 show the mixture compositions of SHCC and concrete used in the current study. The mix design of the SHCC was tailored based on a SHCC mix used in previous projects [10]. Fig. 4 shows the typical tensile stress strain curves of the SHCC. The modified SHCC matrix has a water-to-binder ratio of 0.4 and a filler-to-binder ratio of 0.5. Blast furnace slag (BFS) cement CEM III/B 42.5 N from ENCI (the Netherlands), consisting of 20–34 % clinker and 66–80% BFS, was used as binder and finely grinded limestone powder Calcitec® from Carmeuse (Belgium) was used as filler. Silica fume was added to increase the bond strength between PE fiber and matrix. A polycarboxylate-based superplasticizer MasterGlenium 51 produced from BASF (Germany) with 35.0% solid content by mass was used to reach desired workability. The fiber used in this study is Ultra-high-molecular-weight polyethylene (UHMWPE) fiber with a length of 6 mm and diameter of 20 microns. The healing agent (HA) used is the self-healing bio-polymeric particles from Basilisk (the Netherlands). The HA is made of a poly-lactic acid (PLA) derivate matrix, bacterial spores of Bacillus cohnii-related strains and growth-required nutrient inorganic salts.

Table 1. Mixture compositions of SHCC [unit in kg/m^3].

Constituent	kg/m^3
CEM III/B 42.5R	842
Silica fume	94
Limestone powder	468
Water	374
PE fiber (vol.%)	10 (1.0)
Superplasticizer	3
Healing agent	21

Table 2. Mixture compositions of concrete [unit in kg/m3].

Constituent	kg/m^3
CEM I 52.5R	260
Sand 0.125-0.25 mm	79
Sand 0.25-0.50 mm	256
Sand 0.50-1.00 mm	256
Sand 1.00-2.00 mm	158
Sand 2.00-4.00 mm	99
Sand 4.00-8.00 mm	394
Gravel 6-16 mm	729
Water	156
Superplasticizer	0.26

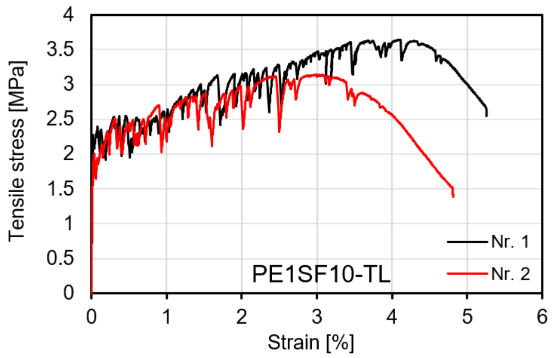


Fig. 4. Tensile stress-strain curve of the mixture used in the precast formwork.

All the hybrid beams in the current study were casted in 2 steps. In the 1st step, SHCC cover (Fig. 5) were prepared and cured for 14 days in a climate room before casting of concrete. In the second step, SHCC cover were first taken out from the climate room and then placed into plywood mould. Inside the SHCC cover, reinforcement cages were placed with appropriate spacers. After the preparation, the concrete casting was then performed and compacted using a vibration needle. The hybrid beams were then cured for 28 days in sealed conditions before testing. Reinforced Concrete (reference beam) was cast along with this second phase.

Fig. 5. Precast U-shape self-healing SHCC covers. The keys inside the cover were designed to enhance the interface bond strength between the cover and the core.

2.3 Testing

All the beams were tested in a four-point bending test setup (Fig. 6) under displacement control at a rate of 0.01 mm/s. The deformation of the beams was measured within the constant bending moment region by using both the Linear Variable Differential Transformer (LVDTs) and Digital Image Correlation (DIC) at both sides. The beams were first painted in white and sprayed with a black speckle pattern by using an air gun. Images for DIC were captured throughout the loading for each 10 seconds. The resolution of the images is 0.08 mm/pixel. Post-processing of DIC results was carried out with a free version of GOM Correlate.

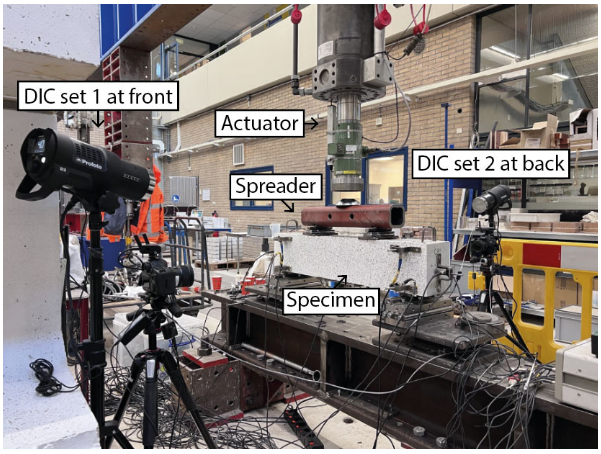


Fig. 6. Experimental setup of the four-point bending test.

3 Results and discussion

Figs. 7-9 shows the crack patterns in the constant bending moment region around first-cracking, reinforcement yielding and reaching ultimate loads for all the tested beams. As can be seen, all the beams failed in flexural tension as designed, which is characterized by the formation of flexural cracks at the tension side and the crushing of concrete at the compression side. It can be clearly seen from the crack patterns that the hybrid beams formed significantly more cracks than the reference beam. Instead of forming only a few large cracks as shown in Fig. 7, the hybrid beams with the self-healing SHCC cover formed closely spaced fine cracks across the constant bending moment region. However, the effect of having the shear-key at the bottom interface is not obvious, for that both hybrid beams showed similar crack pattern. The dot plot right to the crack pattern shows the location and the width of all individual cracks present at respective load step. As can be seen, the distribution of the cracks is rather uniform, and the opening of the cracks were nicely controlled. Even at the maximum load, most of the cracks stayed below 0.3 mm.

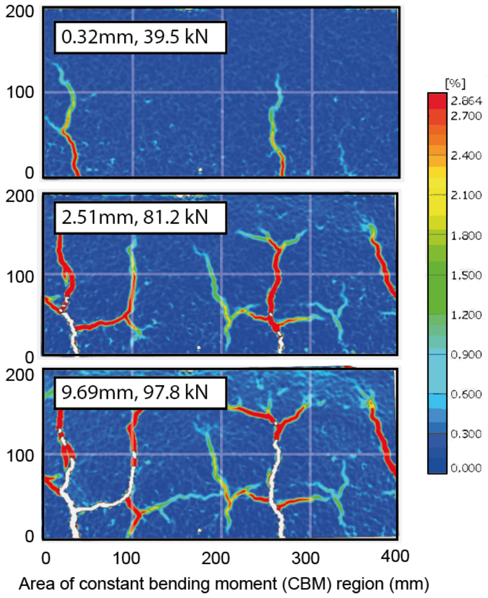


Fig. 7. Crack pattern response of the reference beam. The colormap on side shows the major strain calculated by DIC.

Fig. 10 shows the comparison of load-deformation response and crack development between the beams. As can be seen from the solid lines, load-deflection relation of the hybrid beams are much different than that of reference reinforced concrete beam. Althought the ductility of the hybrid beams are lower than the reference beam, the load bearing capacity of the hybrid beams are around 45-60% higher than the reference beam. While the reference beam experienced a maximum load of 98.3 kN, the hybrid beams reached 145.1kN and 159.1 kN, respectively. The increase in load bearing capacity is expected to be provided by the U-shape SHCC cover in the hybrid beams. Though the thickness of the cover is only 15 mm, the tensile stresses of the SHCC can still contribute significantly to the bending moment as it is located at the outermost of the beam. Also, it can be seen that the interface properties between the cover and the core influences a lot the structural response of the overall beam. With additional mechanical resistance provided by the shear-key at the bottom interface, the load carrying capacity was 14 kN higher, which is expected to be the result of a more synchronous behavior between the cover and the core. More SHCC were thus activated to carry the tensile load. This is also evident from Fig. 12 that there are more cracks formed in the hybrid beam with bottom shearkey at all deflection levels.

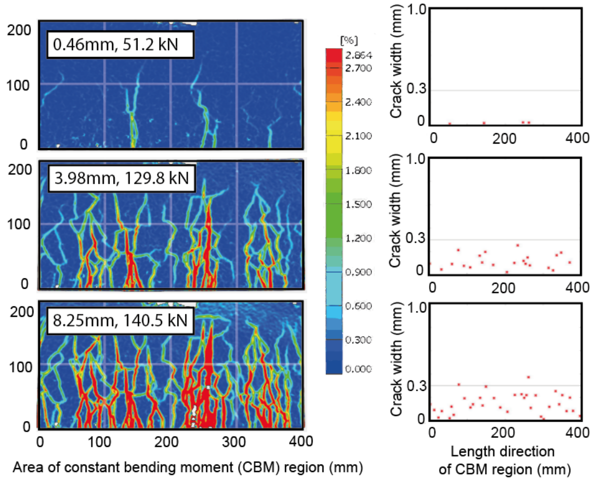


Fig. 8. Crack pattern response of the hybrid beam without bottom shear-key.

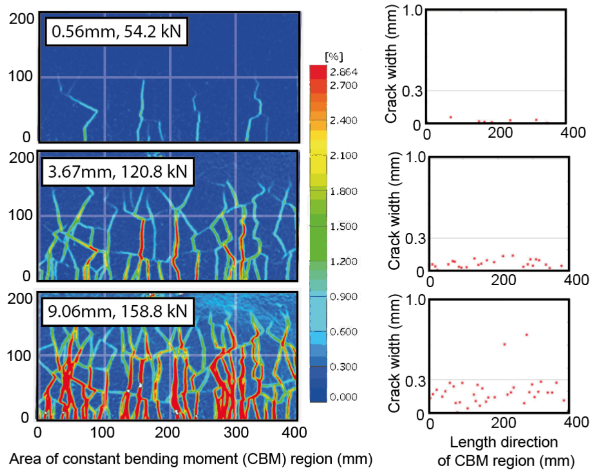


Fig. 9. Crack pattern of the hybrid beam with bottom shear-key.

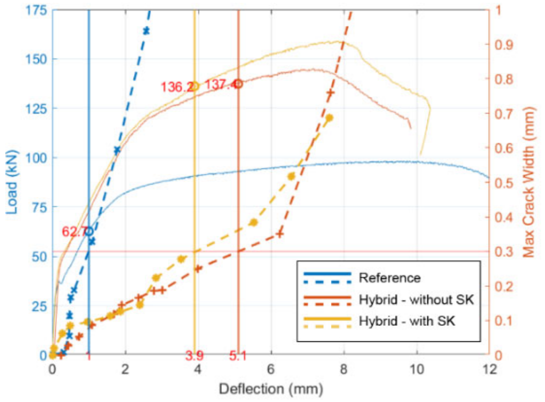


Fig. 10. Load-deflection-max crack width response of the tested beams.

More importantly for the aims of this study, it can be seen that both hybrid beams show improved crack width control ability. The width of the cracks along the bottom edge of the beam exceed 0.3 mm in reference beam at the load of 62.7 kN, while the hybrid beams with and without the shear-key at the interface limited the crack width development to 0.3 mm until the loads of 136.2 kN and 137.4 kN, respectively, reaching more than 90% of their ultimate capacity. Fig. 11 shows the development of both the maximum crack witdh and the average crack width in the two hybrid beams. It can be seen that though the maximum crack width inceases quickly when the beams are reaching their capacity, the average crack width, which represents a more generic situation of all the cracks, only increase slowly. The average crack width stay below 0.2 mm until the end of the tests.

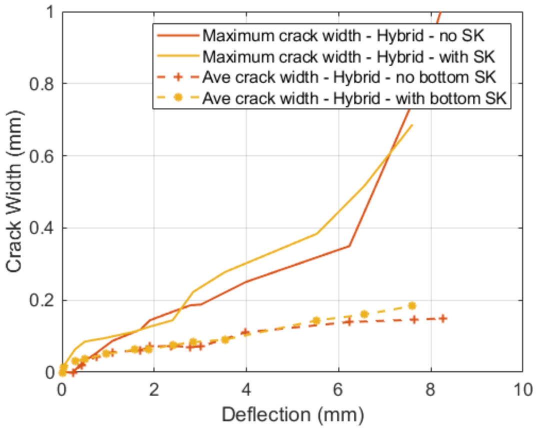


Fig. 11. Development of maximum and average crack width of the two hybrid beams.

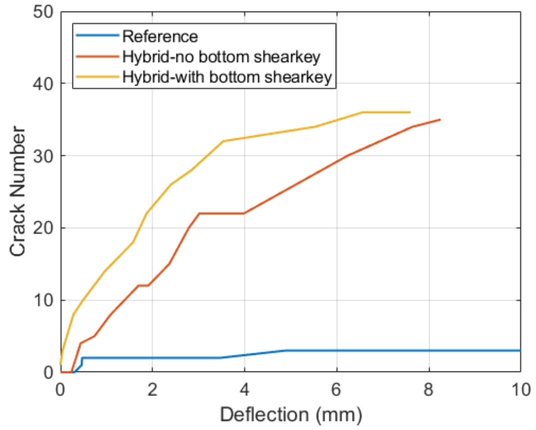
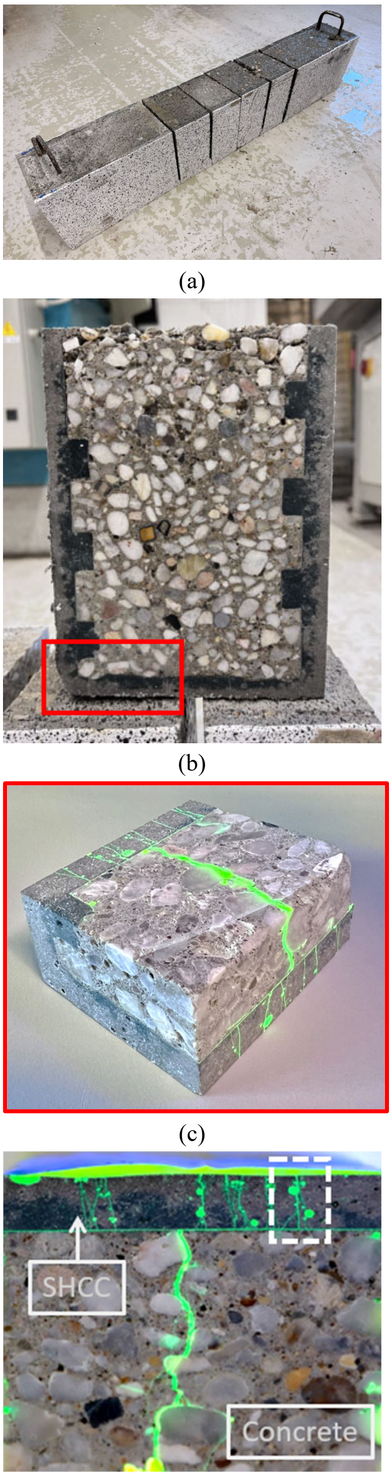


Fig. 12. Development of crack number of all tested beams.

After the structural tests, the tested beams were also sawed into segments for crack width analysis as shown in Fig. 13a. Fig. 13b shows the cross-section of a segment of the sawed beam. Fig. 13c shows a corner-piece from a beam segment after epoxy impregnation. As can be seen, the cover successfully distributed a major crack from concrete to multiple parallel fine cracks in the cover at both the bottom and the lateral sides of a hybrid beam. Fig. 13d is a top view of Fig. 13 c, which shows clearly that the crack distributing effect of the cover layer. With a much-reduced crack width, it is expected that healing could proceed faster and to a greater extend.



(a)

(b)

(c)

(d)

Fig. 13. (a) Beams after sawing. Each segment of the sawed beams has a length of roughly 10 cm; (b) Cross-section of one segment; (c) A further trimmed piece at the corner of a segment after epoxy impregnation; (d) Zoom-in view of crack propagation from concrete to SHCC cover.

As a preliminary study, the beam segments were also stored in a climate room (20°C and ≥ 98% RH) to facilitate healing. After 2 months, the segments were taken out from the climate room and were dried and impregnated with epoxy. Afterwards the beams were also sawed to expose the cross-section of the cracks in the self-healing cover. Fig. 14 shows the crack pattern in the cover after healing. An indicative location where

Fig. 14 was taken is marked in Fig. 13d. But of course, the image was taken from another specimen which has experienced healing. As can be seen, for cracks passing through a healing agent, partial sealing was observed; and it is found that the sealing happened preferably inside the cracks but not at the crack mouth. The extent of healing was also found to be dependent on the crack width. The quantitative evaluation of crack sealing is still underway. The results will be presented during the conference.

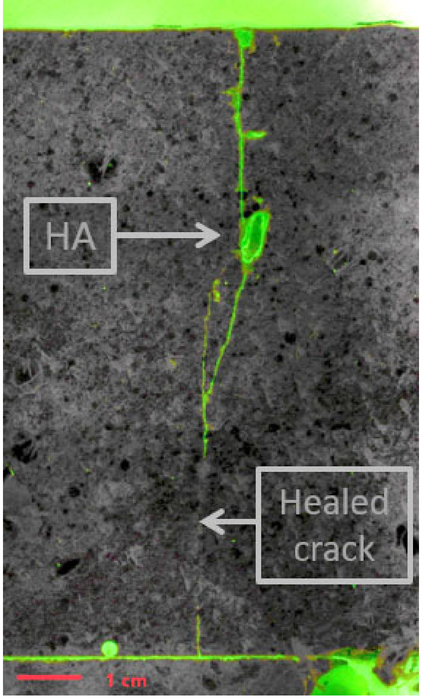


Fig. 14. Optical microscope image of an epoxy impregnated beam segment after 2-month healing.

4 Conclusions

An experimental study was performed aiming to investigate the structural behavior of reinforced concrete beams with a self-healing cover made with bacteria embedded SHCC. Structural behavior, crack pattern and crack width development during loading were compared to the control reinforced concrete beams. Results show that beams with self-healing cover possessed higher load bearing capacity and an improved cracking behavior as compared to the control beam. With a 15-mm-thick layer of SHCC, the maximum crack width of the beams exceeded 0.3 mm at approximately 136 kN load and a deflection of 4 mm, whereas in the control beam it exceeded 0.3 mm at only 63 kN load and a deflection of 1 mm.

It is thus concluded that the beams with self-healing cover zone developed in the current study possess an improved crack control ability at the expense of minimal additional cost. The reduced crack width is expected to largely facilitate crack sealing in the cover zone, which may eventually lead to an extended service life of the whole structure.

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