Evaluation of the performance of self-healing concrete at small and large scale under laboratory conditions

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Abstract

HEALCON is an EU-FP7 project which aims to develop self-healing concrete to create durable and sustainable concrete structures. While during the first years of the project the self-healing materials (including the healing agents and suitable encapsulation methodologies) and monitoring techniques were designed and tested at lab-scale, large scale elements have been tested near the end of the project to verify the feasibility and efficiency of the self-healing concrete under conditions closer to reality.

For this paper, two types of healing agents were investigated for use in mortar and concrete. The first type of healing agent studied was a coated superabsorbent polymer (C-SAP). It is known that the autogenous healing capacity is increased by incorporation of superabsorbent polymers (SAPs) in mortar/concrete. The agents present in the crack can absorb intruding water, swell and block the crack, leading to immediate sealing, but can also exude moisture to the surrounding concrete environment stimulating healing of the concrete by hydration of unreacted cement particles or by $CaCO_3$ precipitation. The disadvantage of these SAPs in the fresh mortar/concrete mix is however that they absorb large quantities of mixing water, leading to unwanted effects (e.g. loss of workability and macro-pore formation). By coating of the SAPs, we want to eliminate this disadvantage. The fluid bed spraying of the different layers was applied by VTT. A second healing agent studied, is a biogenic healing agent, namely a Mixed Ureolytic Culture (MUC). This type of healing agent was developed by Avecom in order to reduce the cost associated with the production of pure bacterial strains. This mixed ureolytic culture is moreover self-protecting and does not need any further encapsulation.

At first, the performance of the healing agents itself was evaluated. For the coated SAPs, the swelling performance and swelling rate were determined, showing that the coating can limit the uptake of water during the first 10-15 minutes. For the MUC, the ureolytic and $CaCO_3$ precipitating capacity was determined, immediately after production of the MUC and after 3 months of storage.

The results show the potential of these mixed cultures to be used as self-healing agent in mortar/concrete, but also show a decrease of their effectiveness with time.

Subsequently, the healing agents were incorporated in mortar mixes at UGent. A dosage of 1 wt% relative to the cement content caused a large reduction of the mechanical properties of the mortar (up to ~ 50%), except for the coated SAP. The sealing efficiency was evaluated with the water flow test, as designed by one of the project partners in HEALCON. The performance of reference mixes was compared to that of self-healing mixes with SAP, coated SAP or MUC (+ urea). Results showed that for cracks with a width less than 0.150 mm, all mortars were sealed (almost) completely after storage for 28 days in wet-dry environment (12 h wet – 12 h dry) after crack creation. For cracks with a larger width, differences were noticed between the different specimens. Moreover, also the immediate sealing effect induced by the presence of SAPs could be noticed. It has to be noted however that the crack width plays an important role but is varying along the crack length (within a specimen) and between specimens, making the analysis more difficult.

In order to extend the application to concrete, self-healing and reference reinforced concrete beams (2500 x 400 x 200 mm) were produced at the Danish Technological Institute. The self-healing concretes contained coated SAPs or MUC. Moreover, the beams were equipped with corrosion sensors that are connected to a wireless monitoring system, developed by the Technology-Transfer-Initiative at the University of Stuttgart. The multi reference electrodes (MuRE) were installed alongside the reinforcements and measure the corrosion potential at certain positions. Data is collected in sufficiently dense intervals by battery powered nodes that transmit the data wirelessly to a base station and further on to a database where it can be accessed through a web based application for data analysis over the internet.

At the age of 28 days, three-point bending cracks up to 0.6 mm were created in the beams. Subsequently, the beams were regularly sprayed with water (four times one hour per day) for 6 weeks and afterwards, the beams were, once a week, exposed to 3 wt% NaCl solution for 24 h. Evaluation of the self-healing performance by microscopic analysis (crack microscopy and analysis of thin sections) showed that for the reference beam and beam with MUC no significant healing could be noticed (probably because of insufficient supply of nutrients for the bacteria). For the beams with coated SAPs, the smaller cracks (0.1 and 0.2 mm) were partly closed. Continuous corrosion monitoring showed corrosion in the reference and MUC beams already after the first exposure to NaCl solution. Onset of corrosion was delayed in the case the beams contained coated SAPs.

Introduction

HEALCON was an EU-FP7 project, started in January 2013 and finished in December 2016, coordinated by Prof. Nele De Belie (Ghent University). The acronym refers to the development of self-HEALing CONcrete to create durable and sustainable concrete structures. One of the final objectives of this project was to demonstrate the self-healing technologies, developed by the project partners and tested first at lab-scale, in a large scale test at conditions close to reality, using the developed (non-destructive) technologies for evaluating the self-healing efficiency.

In this paper, we focus only on the use of two types of healing agents in self-healing mortar/concrete: (1) coated superabsorbent polymers and (2) a mixed ureolytic bacterial culture, and show the progress made from product development to incorporation of the healing agents in small and large mortar/concrete elements in order to test the healing efficiency in laboratory conditions.

Healing agents

Coated superabsorbent polymers (C-SAP). Superabsorbent polymers have the intrinsic property to absorb large quantities of water. While this is the reason why they are applied in concrete (originally for internal curing and later to promote self-healing), the high swelling capability can lead to inferior concrete properties. By absorbing concrete mixing water, the consistency of the concrete is lower and at the moment of SAP desorption, macro-pores are formed for mixes with high w/c ratios, both being unwanted effects. To overcome the disadvantage of swelling at the moment of mixing, HEALCON partners proposed to use (1) pH sensitive hydrogels [1] or (2) coated SAP particles. In this paper, we will focus on the development and use of coated superabsorbent polymers.

A commercially available superabsorbent polymer (d_{50} = 343 µm) was coated by means of fluid bed spraying. The coating consisted out of three layers:

- Polyvinylbutyral (primer), applied on SAP to induce wetting of the barrier polymer layer, ~8 wt-%
- Cyclo-olefin copolymer (barrier), ~12 wt-%
- Sol-gel derived $SiZrO_2$ topcoat (adhesion layer), < 4 wt-%

SEM images of an uncoated and coated SAP particle are shown in Figure 1. Very few holes can be detected in the coating and some agglomeration of particles occurred. Particle size analysis showed that the d_{50} increased up to 467 µm by coating of the SAP particles.

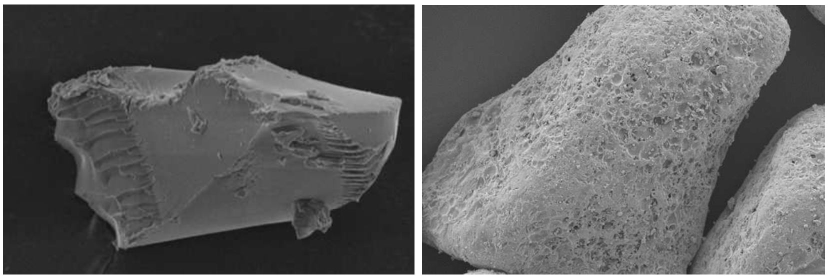

Figure 1. Uncoated (left) and coated (right) SAP particle.

In order to assess the water uptake of the SAPs, a swelling test in demineralized water and cement filtrate was performed according to the filtration method [1]. The results are tabulated in Table 1. The results clearly show that the fluid uptake by the SAPs after 4 hours is almost the same for the uncoated and coated SAPs.

Table 1. Water uptake by the SAPs after 4 hours, determined via the filtration test

Demineralized water		Cement filtrate	
SAP	**C-SAP**	**SAP**	**C-SAP**
252 g/g SAP	161g/g coated SAP = 212 g/g SAP	31 g/g SAP	25 g/g coated SAP = 33 g/g SAP

In order to determine the extent to which the swelling can be delayed by the coating, an additional test was performed. The swelling rate was determined by measuring the volume change of the swollen SAP in the different solutions at regular time intervals [2]. The results, presented in Figure 2, show that the absorption of water is slower for the coated SAPs. However, even within the first 10 minutes, water uptake could not be completely prevented by the coating. After 10-15 minutes, coated SAPs absorbed as much water as uncoated SAPs.

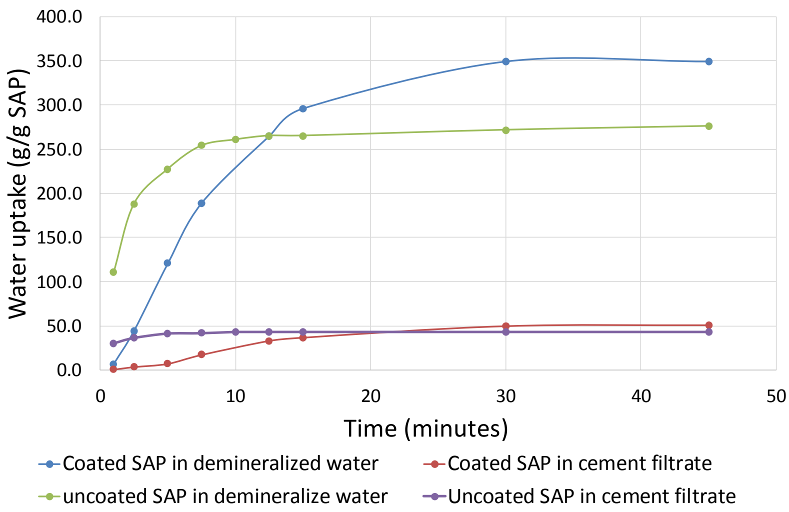

Figure 2. Swelling rate of uncoated and coated SAPs.

Mixed ureolytic culture (MUC). $CaCO_3$ precipitating bacterial spores have shown potential to be used in concrete as healing agent [3, 4]. However, the production of axenic (pure) cultures is associated with a very high cost. In order to keep down a lid on the prices of the bacterial healing agents, ureolytic bacterial spores were produced under non-sterile conditions by imposing a selective pressure combined with a cyclic thermal shock. As inoculum, an activated sludge from the food industry was used and a considerable amount of urea was added to stimulate the urease enzymatic activity. One of the advantages of this product is that no further encapsulation is necessary. A comparable material (called CERUP) was already investigated earlier by Silva [5].

The MUC showed a good ureolytic activity (99% of urea hydrolyzed after 24 hours), specific ureolytic activity (13.6 g urea hydrolyzed/(g Volatile Suspended Solid·h)) and $CaCO_3$ precipitation capability (0.4 g $CaCO_3$/(g VSS·h)). However, when stored for 3 months the MUC was still able to germinate, but the ureolytic acitivity decreased slightly while the $CaCO_3$ precipitation capability decreased considerably.

Performance of self-healing mortars

Mortar mix design. The healing agents as mentioned above have been incorporated in mortar in order to test their influence on the mortar properties and to test the sealing efficiency. The composition of the mortars is indicated in Table 2. For the mixes with MUC, extra urea was added in the mix as precipitation precursor. In order to compensate for the uptake of water by the uncoated SAPs, extra water was added to these mixes (20 g/g SAP). In contrast, no extra water was added in the mixes made with coated SAP. These mixes lost however partly their consistency (flow value of 145 mm instead of 190 mm for the reference mixes), indicating that the coating is not completely effective within the casting time.

Table 2. Mortar mix design (in g)

Material	REF	SAP	C-SAP	MUC
CEM I 42.5 N	450	450	450	450
CEN standard sand	1350	1350	1350	1350
Water	225	225 + 90	225 + 0	225
Healing agent	0	4.5	5.85	4.5
Urea	0	0	0	22.5

Influence on hardened mortar properties. Flexural and compressive strength tests were performed according to EN 196-1 in order to investigate the effect of the healing agent on the mechanical properties of the mortar. As can be seen in Figure 3, a quite high strength reduction is obtained, but the dosage of healing agents is also quite high in the mortars (1 wt% relative to the cement content). For uncoated SAPs, the bending and compressive strength decrease respectively with 37% and 54% compared to the values for the reference mix. With coated SAPs, the reduction is less (respectively 23% and 24%). This can be due to the coating, but also due to the lower water content of the mixes with coated SAP (no extra water was added, as would be the ideal case when the coating is completely impermeable and not rupturing during the preparation phase). Addition of MUC and urea cause the largest effect on the strength properties (43% and 56% reduction respectively for the bending and compressive strength). We expect, however, that addition of comparable dosages of healing agent (relative to the cement content) in concrete will not affect the mechanical properties to such a large extent.

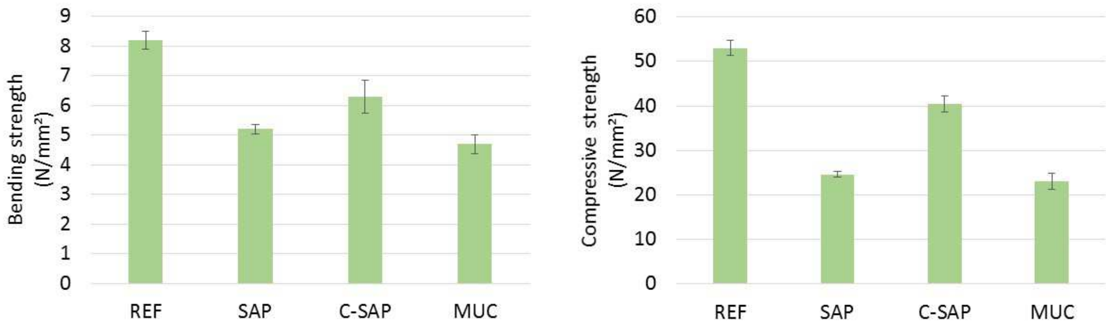

Figure 3. Effect of the addition of uncoated / coated SAP and MUC on the mechanical properties of mortar.

Self-sealing efficiency. The sealing efficiency of the different self-healing systems was evaluated by comparing the water flow through unhealed and healed cracks. For this, prismatic reinforced mortar specimens (40 x 40 x 160 mm, composition as described in Table 2) were made which include a hole (∅ 5 mm) just above the reinforcement level (2 bars ∅1 mm located at 10 mm from the bottom side). The specimens were demoulded one day after fabrication and were sealed cured at 20 °C. At 28 days, cracks were created by a crack width controlled three-point bending test (aimed crack width after unloading ~ 0.150 mm). Subsequent crack healing was stimulated by subjecting the specimens to 28 wet-dry cycles (12 h wet – 12 h dry).

Water flow (WF) tests were performed immediately after crack creation and after healing. A detailed description of the test procedure can be found in [1], but in short, the test works as follows: water at a pressure of 0.05 bar flows through the hole in the specimens and leaks out of the crack in case the crack is not well healed. The amount of water, coming through the crack, is weighed and registered in function of time. Based on the water outflow after 15 minutes (W) obtained before ($W_{unhealed}$) and after (W_{healed}) healing a sealing efficiency (SE) is calculated.

$$SE_{WF} = \frac{W_{unhealed} - W_{healed}}{W_{unhealed}} \; x \; 100\%$$

Before execution of the water flow tests, the crack width was measured at different places along the crack length using a stereomicroscope. It has to be mentioned that the width of the cracks is not a fixed value. The crack width varies along the crack length and between specimens. Although we strived to obtain a final crack width (after unloading) of ~ 0.150 mm, crack widths (measured at the surface) varied between 0.100 and 0.200 mm for the tested specimens. As the crack width is the main parameter influencing the water flow, the varying crack width complicates the analysis of the test results. Therefore, results were categorized in two series: [0.100 mm – 0.150 mm] (Table 3) and [0.150 – 0.200 mm] (Table 4). In Table 3 and Table 4, the water outflow and the sealing efficiency is tabulated for the different types of self-healing mortars and crack widths. It can be clearly seen that for all types of specimens, the sealing efficiency is (almost) 100% for crack widths less than 0.150 mm, while for higher crack widths the sealing efficiency decreases. Reference specimens containing no healing agent only have a sealing efficiency of 50% for cracks of around

0.160 mm. With SAPs and for comparable crack widths, the sealing efficiency is much higher (~ 95%) showing the stimulation of autogenous healing by the presence of these superabsorbent particles. For the specimens with coated SAPs, the sealing efficiency is lower (~ 49%), but this is due to the fact that the average crack width of these specimens is much higher (~ 0.190 mm). These findings all correspond with the microscopic evaluation of the crack closure. At the surface, cracks less than 0.150 mm wide are closed, while cracks more than 0.150 mm are only partly closed (except for the SAP specimens with a crack width of ~ 0.155 mm, for which the crack is completely closed).

Table 3. Water outflow and sealing efficiency in function of crack width [0.100 – 0.150 mm] and type of healing agent used.

Healing agent	Average crack width	$W_{unhealed}$	W_{healed}	SE_{WF}
REF	~ 0.120 mm	2.3	0	100%
SAP	~ 0.140 mm	2.4	0	100%
C-SAP	~ 0.100 mm	0.3	0	100%
MUC	~ 0.135 mm	13.0	0.8	94%

Table 4. Water outflow and sealing efficiency in function of crack width [0.150 – 0.200 mm] and type of healing agent used (no results available for the MUC mortars in the crack width range of [0.150 – 0.200 mm]).

Healing agent	Average crack width	$W_{unhealed}$	W_{healed}	SE_{WF}
REF	~ 0.160 mm	299.2	149.0	50%
SAP	~ 0.155 mm	13.2	0.6	95%
C-SAP	~ 0.190 mm	544.7	279.5	49%

Besides the fact that the presence of superabsorbent polymers stimulates autogenous healing processes by providing water to the surrounding cement matrix, these superabsorbent polymers can also induce a direct sealing effect immediately after crack formation. The particles present at the crack faces can absorb intruding water, swell and block the crack from further ingress of water. The results of the water outflow in Table 4 confirm this: the difference between the water outflow of reference and SAP specimens (having almost the same crack width) before healing is quite high indicating an immediate sealing efficiency due to the presence of SAPs: $(W_{REF,\ unhealed} - W_{SAP,\ unhealed})/W_{REF,\ unhealed} \times 100\% = 96\%$. From the results tabulated in Table 3 and for the C-SAP, it is more difficult to make the calculation as the crack width of the reference specimens and the SAP/C-SAP specimens is quite different and the crack width has a large effect on the water flow results.

Performance of self-healing concrete

Concrete mix design. As reference concrete, a concrete mix design typical for Danish infrastructure projects was chosen (Table 5). The concrete had a strength class C40/50 and the binder consisted of CEM I 42.5 N cement (sulfate resistant and extra low alkali content) and fly ash. The water/cement ratio was 0.40 (calculated with an activity factor of 0.5 for fly ash). The consistency class was S4 and the target air content was 6%. Sea dredged sand and granitic coarse aggregates were used and the additives were Glenium SKY 631 superplasticizer and Amex SB 22 air entraining agent from BASF.

For the MUC concrete, 5 kg of MUC per m^3 concrete was added "on top of" the reference concrete and the superplasticizer dosage was adjusted to reach similar consistency. The C-SAP concrete was designed as a self-compacting concrete in order to minimize the time needed for casting, as the C-SAP concrete lost consistency rather quickly, due to water uptake by the SAP particles. Although the purpose of the coating on the SAP particles is to minimize the uptake of mixing water, extra water was added to the mix design, as the coating partly loses its function after 10 minutes. The different mix designs appear from Table 5.

Table 5. Concrete mix design in kg/m³.

Material	REF	C-SAP	MUC
Healing agent	0	5.2	5
CEM I 42.5 N	300	330	300
Fly ash	100	110	100
0/4 mm sand	680	760	680
4/8 mm granite	295	300	295
8/16 mm granite	800	600	800
AEA	1	0	1
SP	2.3	2.5	2.7
Water	137	196	137

Influence on fresh and hardened concrete properties. Regarding the fresh concrete properties, the REF and MUC concrete both had a slump around 180 mm (with slightly higher superplasticizer dosage for the MUC concrete) and after one hour this slump value was maintained. The C-SAP self-compacting concrete had a slump flow of 550 mm, but it lost consistency rather quickly due to water uptake by the SAP particles. The coating was only able to delay the water uptake process for 10 minutes and 30 minutes after mixing, the concrete had lost its workability. The air content amounted to 7.0 and 6.6 % for the REF and MUC concretes respectively, while the C-SAP concrete was not air entrained as the frost resistance of the concrete containing SAPs should be higher than a concrete without SAPs [6, 7]. The air content of the C-coated SAP mix was only 2.5%.

The hardened concrete properties are shown in Table 6. For the REF and MUC concrete, the compressive strength was measured on cylinders (∅ = 100 mm, h = 200mm) at 7, 28 and 56 days (EN 12390-3) and also the chloride migration coefficient (28 and 63 days) (NT Build 492), air void parameters (specific surface and spacing factor) (EN 480-11) and freeze/thaw resistance (scaling after 56 freeze/thaw cycles) (CEN/TS 12390-9) were determined. It is clear that the hardened concrete properties are not affected by the addition of MUC to the concrete (5 kg/m^3 concrete). For the C-SAP concrete, only compressive strength at 7 and 28 days was measured. The strength of the C-SAP concrete is similar to the REF, even though extra water was added. Moreover, it should be considered that this concrete was not air entrained.

Table 6. Hardened concrete parameters.

Parameter	REF	MUC	C-SAP
7-days strength (MPa)	30.7	30.5	31.3
28-days strength (MPa)	51.8	50.4	51.1
56-days strength (MPa)	62.7	63.7	*
CMC, 28 days (x 10^{-12} m^2/s)	20.6	16.3	*
CMC, 63 days (x 10^{-12} m^2/s)	5.8	5.4	*
Specific surface (mm^{-1})	29.5	35.3	*
Spacing factor (mm)	0.13	0.12	*
Scaling, 56 cycles (kg/m^2)	0.04	0.02	*

* not tested

Design of the beams, including the installation of sensors. Concrete beams with dimensions 2500x400x200 mm were cast of each of the three mix designs. The beams were reinforced with four 10 mm ribbed steel bars with a cover of 55 mm (4).

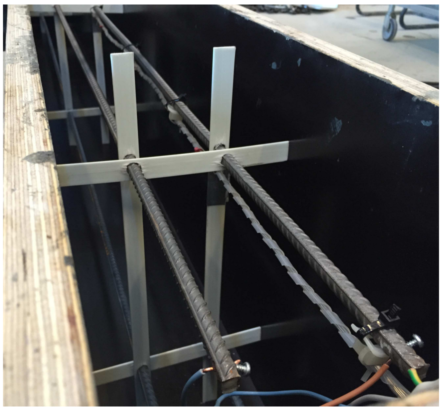

Figure 4. Formwork with rebars and MuRE sensor installed below one rebar.

A wireless monitoring system was installed and the beams were instrumented with sensors for continuous monitoring. The self-healing efficiency was indirectly monitored with electrometers attached to the MuRE (Multi Reference Electrode) sensors [8] which were embedded into the beams in proximity to the reinforcement (Figure 5). This allowed to monitor the electric potential within the concrete which is affected by electrochemical processes such as reinforcement corrosion. In case of successful self-healing, the cracks in the samples should be sealed, as such no reinforcement corrosion should be measurable in the respective areas. On the other hand, if reinforcement corrosion is detected in the area of a crack, after a supposedly healed specimen has been exposed to chloride solution, the healing was insufficient to protect the reinforcement.

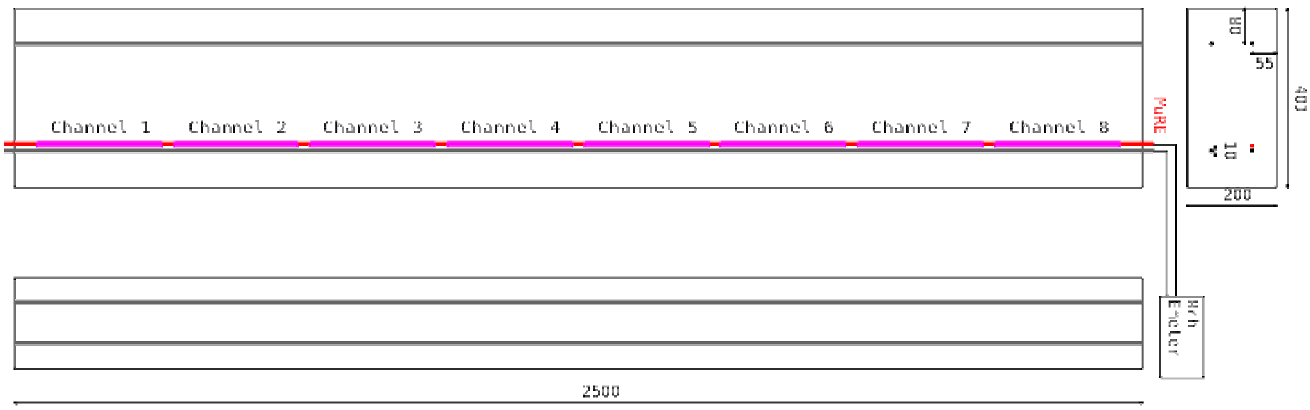

Figure 5. Instrumentation of concrete beam with MuRE sensor (Nickel wire segments, potential measurement against reinforcement) – scale 1:10.

Non-destructive testing procedures. Besides conventional evaluation methods, non-destructive testing methods were used to study the fractural mechanical properties of the concrete to determine the efficiency of the applied self-healing methods. Preliminary experiments within the HEALCON project on small-scale test objects as mortar or concrete beams proved the applicability of different techniques [9, 10]. However, due to the size of the examined concrete beams in this study (2500 x 400 x 200 mm) the scope of NDT techniques is more limited. Ultrasonic transmission measurements with solidly coupled broadband transducers were performed. High voltage pulses, produced by an ultrasonic generator, are introduced into the concrete by a transmitter in form of mechanical waves. The change of its characteristics (travel time, energy, etc.), while propagating through the medium, enables to characterize the material properties in its different states.

Curing and healing procedures. After casting and demoulding, the beams were wrapped in plastic and stored at room temperature to a maturity of 28 days. Cracks with widths ranging from 0.1 to 0.6 mm were then induced in the beams using a customized 3-point bending setup. After crack formation, the beams were subjected to cyclic water exposure (one hour water exposure and four times a day) for a period of six weeks. Following the water exposure period, the beams were exposed to a 3 wt% NaCl solution for 24 hours and this was repeated one week later. Furthermore, cores were drilled through cracks and used for preparation of plane and thin sections for microscopic evaluation of crack healing.

Self-healing efficiency evaluated by visual inspection and microscopy. The crack healing at the surface was evaluated during the cyclic water exposure period both by visual inspection and using a crack microscope. For the REF and MUC beams, no crack healing could be identified (no visual precipitation in the cracks). This was confirmed from the analysis of plane and thin sections, where the cracks appeared empty with only a thin crust of calcite formed along the crack faces (Figure 6).

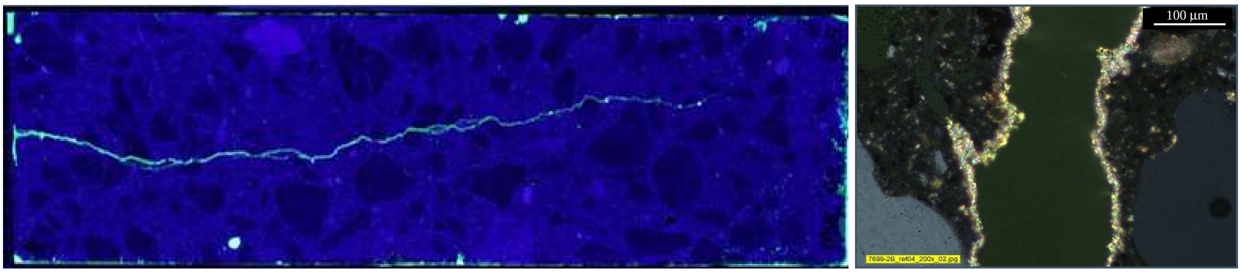

Figure 6. Epoxy impregnated plane section of the reference concrete in UV light showing empty crack (left) and calcite precipitation along crack faces (right).

For the C-SAP beam, the smaller (0.1 and 0.2 mm) cracks seemed to be partially closed in the surface and some white precipitate could clearly be identified (Figure 7). The fact that larger cracks are not healed is not surprising. Our findings correspond quite well with the maximum crack widths which can be closed due to stimulated autogenous healing by SAPs reported in literature [11].

Figure 7. C-SAP beam with a 0.2 mm crack before (top) and after (bottom) 4 weeks water exposure.

Self-healing efficiency by ultrasonic measurements. Known from previous studies [12], e.g. small-scale tests, the ultrasonic transmission method is useful for crack depth determination by picking the onset of the acoustic wave. In order to proof self-healing, a change of the onset time is expected due to (partial) crack closure. Therefore, single-sided ultrasonic transmission measurements at one surface (Figure 8) were conducted for crack widths from 0.4 mm to 0.6 mm during all different states (initial, cracked, healed).

Figure 8. Large-scale beams after water exposure period with installed NDT instruments.

Figure 9 shows the crack depths, examined by time of flight differences of compressional waves, for the MUC and the REF beam for crack widths from 0.4 mm (MUC/REF_04) to 0.6 mm (MUC/REF_06).

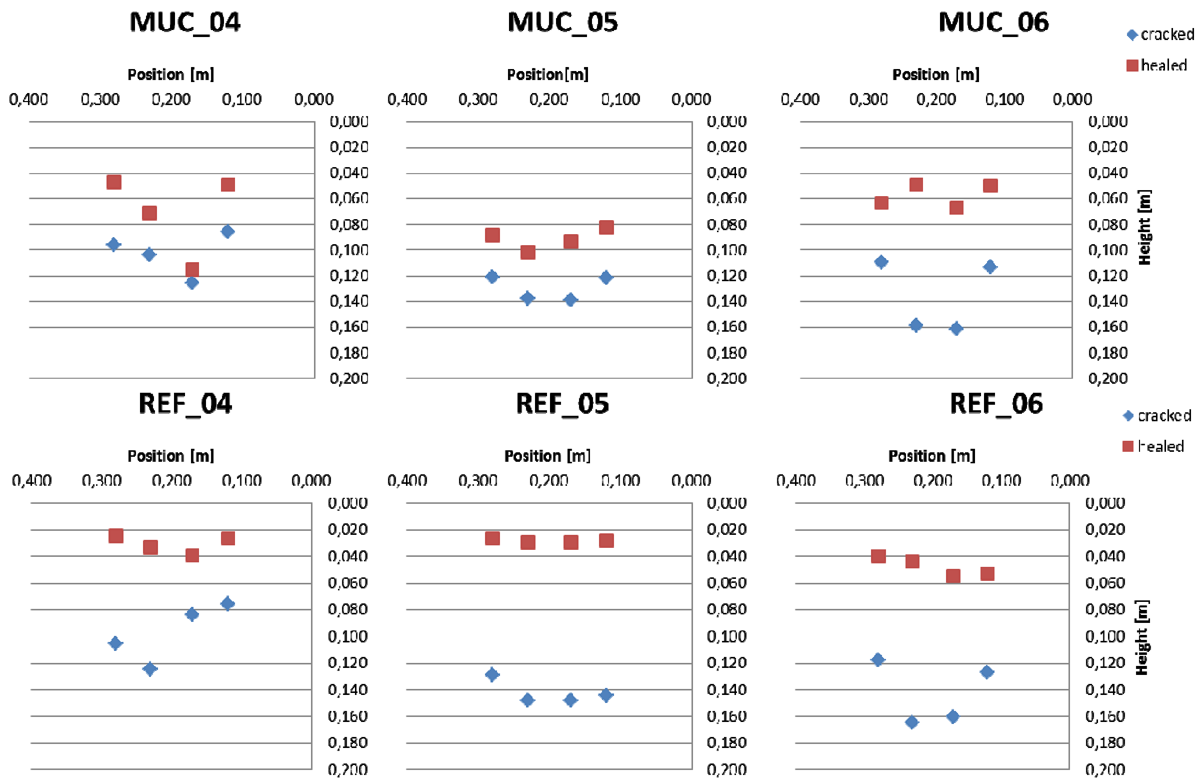

Figure 9. Results of the crack depth examination for the MUC and REF beam by ultrasonic transmission measurements for different crack widths (0.4, 0.5, 0.6 mm). The outer measurements (Position: 0.120 m, 0.280 m) are affected by the design of the test specimen.

The crack depth is determined through the extended detour of the acoustic wave around the crack. It can be noted that with increasing crack width a larger crack depth is identified. Alternative analyses of the crack depth (e.g. visual inspections of drilled cores) confirm these results. After 6 weeks of water exposure and an additional 2 weeks of drying, crack depths vary significantly and no trend is identifiable with regard to the different crack widths as well as between the REF and MUC beams. The decrease of the crack depth after water exposure can be caused by (1) a general crack width reduction, due to shrinkage effects, movement of the specimens or (2) a creation of contact points along the crack, due to sedimentations during water exposure. Further analysis as accumulated energy or frequency content did also not suggest any indications for healing effects.

Self-healing efficiency by continuous corrosion monitoring. In practice, detecting corrosion has been made difficult by the presence of other electrochemical processes, such as an increased electric potential during clear water ingress and suspected oxygen depletion, pre-existent reinforcement corrosion at the time of casting, and suspected electrochemical interaction with the healing agent. These processes would need further study in respect to individual healing agents and applications.

Nevertheless, reinforcement corrosion has been detected and identified in all reference samples without healing agents and in the specimens including MUC. The superabsorbent polymers have been able to significantly delay the onset of corrosion compared to the reference samples. Until now, 4 exposure cycles with NaCl have been performed and no significant increase in potential could be detected.

Table 7. Corrosion detection on different samples.

Sample	**Corrosion detected?**
REF	Yes, during the first 24 h exposure period to NaCl solution
MUC	Yes, during the first 24 h exposure period to NaCl solution
SAP	No, reinforcement was corroding at time of casting, but no significant increase in potential after four chloride exposure periods

Conclusion

In this paper, the first steps forward to test self-healing concrete in large scale elements are described. It includes the production of self-healing agents, self-healing mortar and self-healing concrete and evaluating the effect of the healing agents on (i) the fresh and hardened mortar/concrete properties and (ii) the self-sealing efficiency by different (non-destructive) methods.

The results clearly show that:

(1) Based on the tests in mortar, both healing agents considered here, have potential to be used in self-healing concrete. They induce crack closure and improve the sealing efficiency in comparison to the references. The dosage used here (1wt% relative to the cement content), leads however to a high reduction of the mechanical properties.

(2) Coating of the SAPs is effective only for a small period of time (10-15 minutes). In order to limit the casting time, an SCC mix was designed for this type of self-healing concrete in this study. Ideally, the coating should last for a longer time so that this concrete can be handled more easily.

(3) Addition of ~ 1 wt% of the healing agents (vs. binder content) to concrete has no significant effect on the tested hardened concrete properties.

(4) Cracks up to a width of 0.200 mm partly close for the self-healing concrete beams containing coated SAPs. For the reference beams and beams with MUC, no visual healing could be detected. Possible reasons for the bad performance of the MUC concrete can be related to the dosage of MUC, shelf-life, insufficient availability of urea / nutrients, etc. So, tests are ongoing to improve the healing agent and the concrete design.

(5) The application of non-destructive testing devices confirmed to be a suitable technique to control and monitor the fracture behavior of cementitious test specimens. The variation in the measurement results of the MUC beam after the curing period could however not be related to effective healing.

(6) Continuous corrosion monitoring showed that incorporation of the coated SAPs can delay the onset of corrosion. However, more tests are necessary to validate the results.

From all of this, it is clear that further research is still necessary in order to optimize the healing agents, concrete mix designs, dosage of healing agent (including precipitation precursors and nutrients for the biogenic healing agents) in concrete, etc.

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