PERFORMANCE OF SHCC WITH BACTERIA FOR CONCRETE PATCH REPAIR

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ABSTRACT
The overall performance of concrete patch repair systems depends on the durability of and compatibility between the concrete substrate and the repair material. This paper investigates the performance of a new type of SHCC material with embedded bacteria as a repair material. The bacteria are a healing agent to enhance the durability of the repair system. The bonding strength between the repair material and the concrete was studied by means of both pullout tests and flexural tests. Restrained shrinkage was measured in layered systems with the concrete substrate, whereas the durability of the layered systems was measured by means of rapid chloride migration tests and thermal compatibility tests. Detailed results reported in this paper show the potential of SHCC with bacteria as a concrete patch repair material with improved bonding and durability.

INTRODUCTION

Two important factors determine the overall performance of concrete patch repair systems: the durability and compatibility between the concrete substrate and the repair material. In recent years strain-hardening cement-based composites (SHCC) have been studied as possible repair materials because of their high tensile strain capacity (Li 2009, Zhou 2011, Sierra-Beltran and Jonkers 2012, Sierra-Beltran et al. 2014). This paper investigates the performance of a new type of SHCC with embedded bacteria as a repair material. The bacteria together with an organic source as nutrients for the bacteria are a healing agent immobilized in LWA. This healing agent would enhance the durability of the repair system. Experimental studies were conducted to verify whether the high ductility of SHCC can relieve the shrinkage-induced stresses in the repair layer and in the interface with the concrete substrate, which should reduce interface delamination, supress large repair surface cracks, induce micro-cracking and promote healing of such micro-cracks. The bonding strength between the repair material and the concrete was studied by means of both pullout tests and flexural tests. Restrained shrinkage was measured in layered systems with the concrete substrate whereas the durability of the layered systems was measured by means of rapid chloride migration tests and thermal compatibility tests. Detailed results reported in this paper show the potential of SHCC with bacteria as a concrete patch repair material with improved bonding and durability.

SHCC are materials designed to have large values of strain capacity compared to concrete (Li 1993). The materials are reinforced with a low percentage, 2% or less per volume, of randomly distributed polymer fibres. Under tensile stress SHCC forms multiple fine cracks by the cross-linking effect of the fibres.
In order to control the fracture toughness of SHCC most design mixtures do not include coarse aggregates and only a small amount of fine sand (Li 1993). This characteristic leads to a higher cement and binder ratio and eventually to a high value of shrinkage (Buffenbarger et al. 1998). Sierra-Beltran and Jonkers (2012) reported drying shrinkage strain values of 0.17% to 0.3% for different SHCC mixtures. In similar drying conditions of 20°C and 60% relative humidity, normal concrete has a drying shrinkage strain of

0.04% to 0.0600% (Neville 1995). Due to this high drying shrinkage capacity when applied as a repair material SHCC is expected to crack when subjected to differential shrinkage but it is capable of carrying more tensile load and to accommodate larger tensile strain than other repair systems (Zhou 2011). SHCC is expected to develop multiple cracks instead of delamination from the concrete substrate. Cracking and interface delamination accelerate the penetration of water, oxygen, chlorides and other harmful chemical components into the repair system and into the concrete substrate causing once again damage.

EXPERIMENTS

In this study of the performance of SHCC with embedded bacteria for concrete repair, experimental tests were performed to determine the bonding strength between the concrete substrate and the repair layer, the restrained shrinkage and the durability of this layered system.

Two SHCC compositions were developed and tested: one with embedded bacteria as healing agent and one without. The compositions are presented in Table 1 together with the mix design for the concrete substrate.

In this research healing agent is impregnated in lightweight aggregates (LWA). The healing agent consists of alkali-resistant spore-forming bacteria with calcium lactate as a nutrient source for the bacteria. The healing capacity of this agent in SHCC materials has been described in previous research (Sierra-Beltran et al. 2014, Wiktor and Jonkers 2011).

Table 1: Mix design for layered systems by weight (in Kg/m^3)

Components	Repair Mix 1	Repair Mix 2	Components	Concrete substrate
CemI 42.5N	483	449	CemIII 42.5 LH HS	340
FA	580	538	Sand	836
LP	387	260	Gravel	1017
LWA		123		
Water	420	390	Water	169
SP	21	20	SP	0.7
PVA fibres	22	22		
water-to-binder ratio	0.4	0.4	water-to-binder ratio	0.5

Mechanical performance

Repair mortars compressive and flexural strength

For each repair mortar mixture prisms were casted with dimensions 40 x 40 x 160 mm and thin beams with dimensions 240 x 60 x 10 mm. The specimens were demolded after 24 hours and moist cured in plastic bags at 95% RH 25±2ºC for 28 and 90 days. The prisms were cut into 40-mm cubic specimens for compression tests and the thin beams were cut into specimens with dimensions 120 x 30 x 10 mm for four-point bending tests. The bending tests were performed under displacement control at a loading rate of 0.01 mm/s. The span length of the flexural loading was 110 mm with a 30 mm centre span length. During the tests both the load and the mid-span deflection were recorded.

Interface bonding strength

The tensile bond strength between the concrete substrate and the repair mortar was determined according to NEN-EN 12636 (1999). For the tests the surface of a 28-days old concrete sample was sand-blasted, and then cleaned to remove any dust. Two series of tests were carried out in two different independent laboratories: with and without primer in the interface. Primer is used as an aid to improve the bonding between a concrete substrate and the repair layer. In this research Hechtprimer Cement (from Cugla) was used. It was applied to the clean concrete surface. Immediately after a 12 mm layer of repair material was casted on top. In the second series no primer was applied; instead the repair mortar was casted directly on top of the clean concrete surface. All samples in both series were cured in water for 28 days. Then, a ring groove was drilled through the mortar layer and about 12 mm into the concrete. Cylindrical steel dollies were then glued to the mortar. The tests were done at age 35 days.

Flexural test

A four point bending test is used to examine the structural behaviour and debonding tendency of the composite repair-substrate system. The roughness of the interface between the concrete substrate and the repair material and the curing conditions are considered to have an influence on bond strength and performance of the repair system. However, there is not yet a clear relationship between the roughness parameters and the adhesion of the repair material (Lukovic et al. 2013). The influence of the curing condition has not been reported either. In order to understand the influence of the surface roughness in this paper flexural test are presented with two different surface conditioning: smooth surface and rough surface.

The dimensions of the concrete beam are 200 x 50 x 30 mm. A 20 mm thick repair layer is cast on top. Samples were prepared using each of the repair materials. The concrete beam was cut from a bigger concrete sample casted 3 years before and cured at a climate chamber (50±5% RH and 20±2 ºC). For the samples to be tested with a smooth contact surface this beam comes from the cutting side of the sample. For the rough surface one side of the samples is prepared with a chisel and steel brush to remove the slurry cement from the coarse aggregates. Both types of surfaces were cleaned with high-pressure air. The concrete beams were submerged in water for 3 days. After taking the samples out of water the surface of each sample was dried and the repair layer was casted on top of this contact surface. The composite beams were then covered with plastic and cured for 24 h. After demoulding, the layered system was placed in a climate chamber with 99±1% RH and 20±2 ºC for 27 days.

The bending tests were performed under displacement control at a loading rate of 0.01 mm/s. The span length of the flexural loading was 165 mm with a 55 mm centre span length. During the tests both the load and the mid-span deflection were recorded.

Figure 1: Interface bonding sample

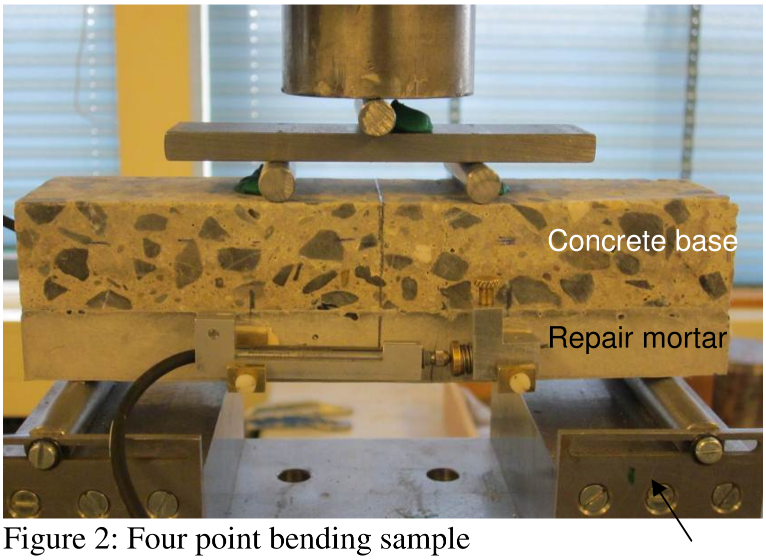

Figure 2: Four point bending sample

Restrained shrinkage

The restrained shrinkage of the two repair materials were also studied by means of a layered system consisting of a concrete substrate and a repair layer. The dimensions of the concrete beams are 500x100x100 mm and the thickness of the repair layer casted on-top is 12 mm. The concrete samples were casted two years before and cured in a climate chamber (50±5% RH and 20±2 ºC). During this curing time any potential shrinkage of the concrete substrate occurs. One surface of the samples was roughened following the same procedure mentioned above. The concrete samples were moisture-cured for 3 days and then the roughened surface was dried. Once the repair layer was casted the samples were wrapped in plastic and cured for 24 hours. After demoulding, the samples were placed in a climate chamber under conditions 50±5% RH and 20±2 ºC. For each layered specimen two dial gauges were used to record the interface delamination in terms of interface vertical separation distance at the end locations of the specimens in terms of drying time.

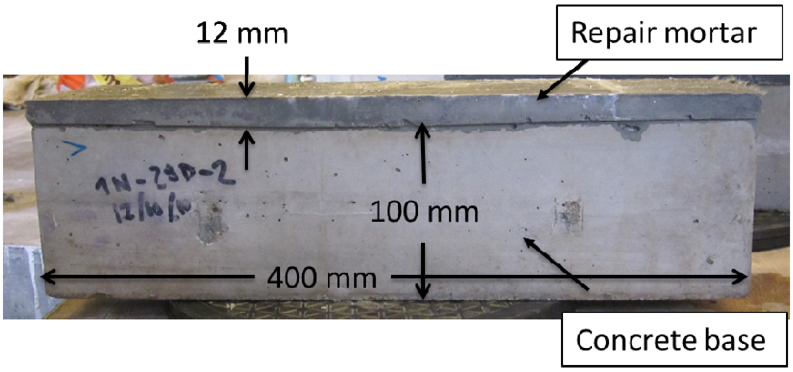

Figure 3: Restrained shrinkage samples

<u>Durability performance</u>

Rapid chloride migration

In this paper the Rapid chloride migration (RCM) test is used to investigate the durability of the composite system in terms of the resistance against chloride penetration in a sample with two layers: a concrete substrate and a repair layer. The influence of the curing conditions in the durability of the layered system is studied by testing samples cured under two different conditions: moist-curing (99±1% RH and 20±2 ºC) and dry-curing (50±5% RH and 20±2 ºC). After 210 days subjected to differential shrinkage, three cylinders with a diameter of 100 mm were drilled out of each composite beam (used in the restrained shrinkage test mentioned above). As shown in Figure 4, the specimen consists of a layer of repair material with a thickness of 12 mm and a layer of concrete with a thickness of 40 mm. The samples were saturated with calcium hydroxide ($Ca\ (OH)_2$) solution for 24 hours after which they were placed in a rubber sleeve and tightened to avoid water to go along the edges of the samples. The samples are then placed in the test setup. The concrete surface is immersed in an anolyte solution while the repair surface is immersed in a catholyte solution. A voltage of 60V is then applied for 24 hours. Once finished the tests, the samples were removed from the solution and from the rubber sleeve and break into two pieces perpendicularly to layer orientation. On the freshly split surface 0.1 M $AgNO_3$ was sprayed and after few minutes white silver chloride precipitated. The precipitated silver chloride represents the chloride penetration depth, from which the migration coefficient is calculated.

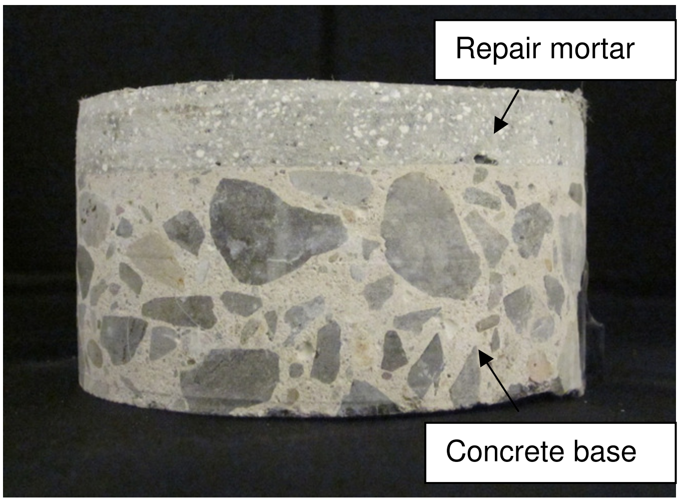

Figure 4: RCM test sample

Thermal compatibility – Freeze and thaw cycles
Samples were prepared as described in section "Interface Bond Strength". Then they were cured for 28 days at a climate chamber (50±5% RH and 20±2 ºC) for 28 days after which they were conditioned in freeze and thaw cycles according to NEN-EN 13687-3 (2002) for 28 days. Then the samples were tested as described above in section "Interface Bond Strength".

The mass loss after freeze and thaw with de-icing salts was also investigated as an indication of thermal compatibility. These layered test samples, similar to those prepared for interface bonding strength, were first cured for 28 days and then cut to smaller sections with dimensions 150 x 150 x 107 mm. The samples were then conditioned according to NPR-CEN/TS 12390-9 (2006) with de-icing salts for 28 days. After this period the mass loss was registered for each sample.

RESULTS AND DISCUSSION

Mechanical performance

Repair mortars compressive and flexural strength
The average compressive strength of the repair Mix 1 at 28 days is 38.5 MPa and of the repair Mix 2 (with bacteria) is 39.8 MPa. Both materials fulfil the compressive strength requirements for repair material of concrete structures Class R3 according to the standards NEN-EN 1504-3 (2005). The average strength is higher for material containing LWA with bacteria and food source. The same effect has been reported by Jonkers and colleagues (2009) and Sierra-Beltran et al. (2012, 2014).
The average flexural strength at 28 days for the repair Mix 2 is 11.1 MPa and the average deflection capacity is 6.7 mm. At 100 days the average flexural strength is 10.9 MPa and the deflection capacity is 5.8 mm. The repair material developed multiple cracking prior to failure. A mid-span deflection of more than 5 mm is considerable greater than the ductility of conventional concrete. This high deflection capacity is typical for SHCC.

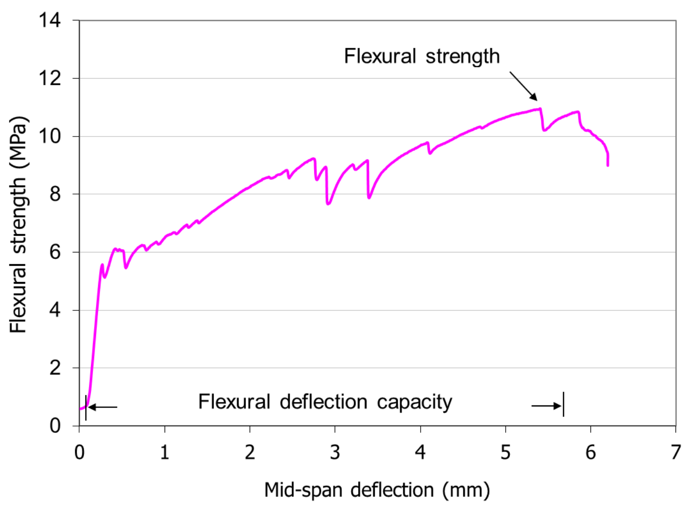

Figure 5: Flexural load-deflection curve of Repair Mix 2 at 100 days

Interface bonding strength
The average bonding strength for the repair mortars is summarized in Table 2. At 28 days, the bonding strength of the repair Mix 2 is higher when a primer was applied prior to casting the mortar. Nevertheless, the lower bonding strength without primer of 1.9 MPa fulfils the requirement for repair material of concrete structures Class R3 (≥1.5 MPa). The repair Mix 1 (without LWA particles – bacteria) achieves a higher bonding strength without primer, 3 MPa. In all the tested samples the failure occurred in the mortars, indicating that the tension strength of the repair mortar without LWA is higher than when these particles are added to the mortar mix.

Table 2: Average bonding strength (in N/mm^2)

Repair material	Water cured for 28 days		Water cured for 28 days + freeze/thaw cycles for 28 days
	With primer	Without primer	Without primer
Mix 1	-	3.0	2.6
Mix 2	2.9	1.9	1.8

Flexural test

The average load-deflection curves for the two surface profiles for the layer systems with repair Mix 1 is presented in figure 6. There is almost no difference in response of the system with different roughness. The same counts for the layer systems with repair Mix 2, as shown in figure 7. Similar results were reported by Lukovic et al. (2013). The average bending force is slightly higher for layered systems with Mix1 and the average deflection capacity is slightly higher for systems with Mix 2. There is a substantial difference between the flexural behaviour of the layered beams with Mix 2 and with Mix 1. The samples with Mix 1 only exhibit a few, localized cracks (as can be seen in few peaks in the flexural load-deflection curves in figure 6) while the samples with Mix 2 behave ductile with multiple micro-cracks prior to failure (as can be seen in the numerous peaks in the flexural load-deflection curves in figure 7). The multiple cracking can be observed in figures 10 and 11.

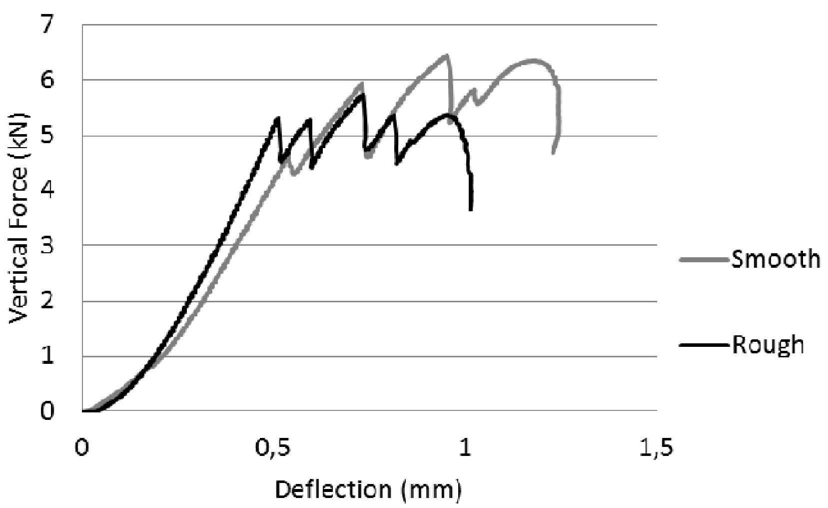

Figure 6: Flexural load-deflection curve of layer system with repair Mix 1 at 28 days

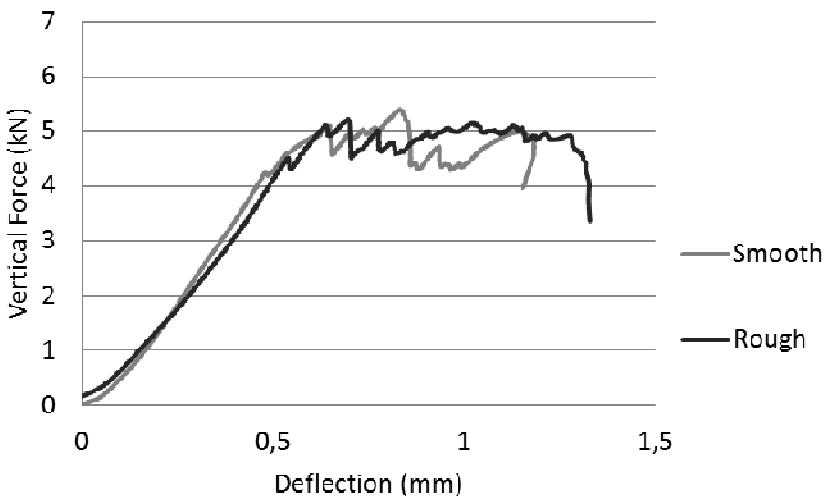

Figure 7: Flexural load-deflection curve of layer system with repair Mix 2 (with LWA) at 28 days

The bonding between both repair mortars and the concrete substrate was excellent and under flexural stress there was no delamination. The layered system behaves as one single material. No delamination could be seen in the interface, even after failure, as can be seen in figures 8 to 11.

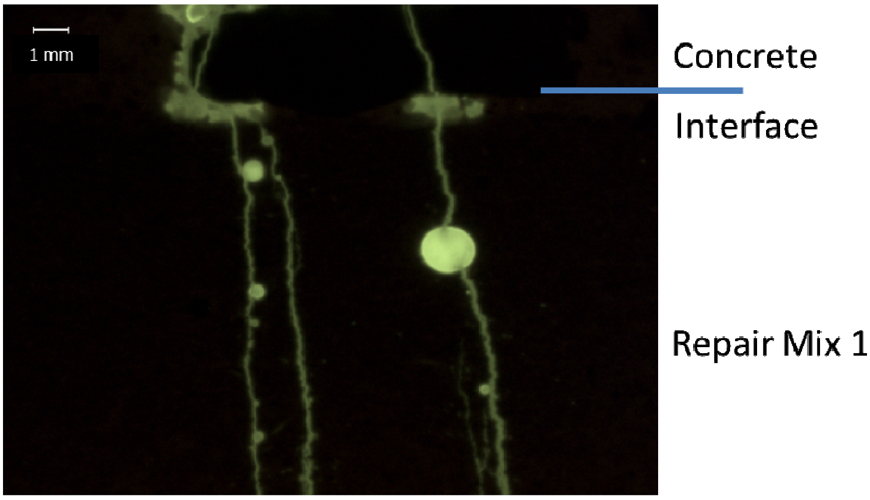

Figure 8: Final crack patterns for smooth interface surface and Mix 1, impregnated with fluorescent epoxy.

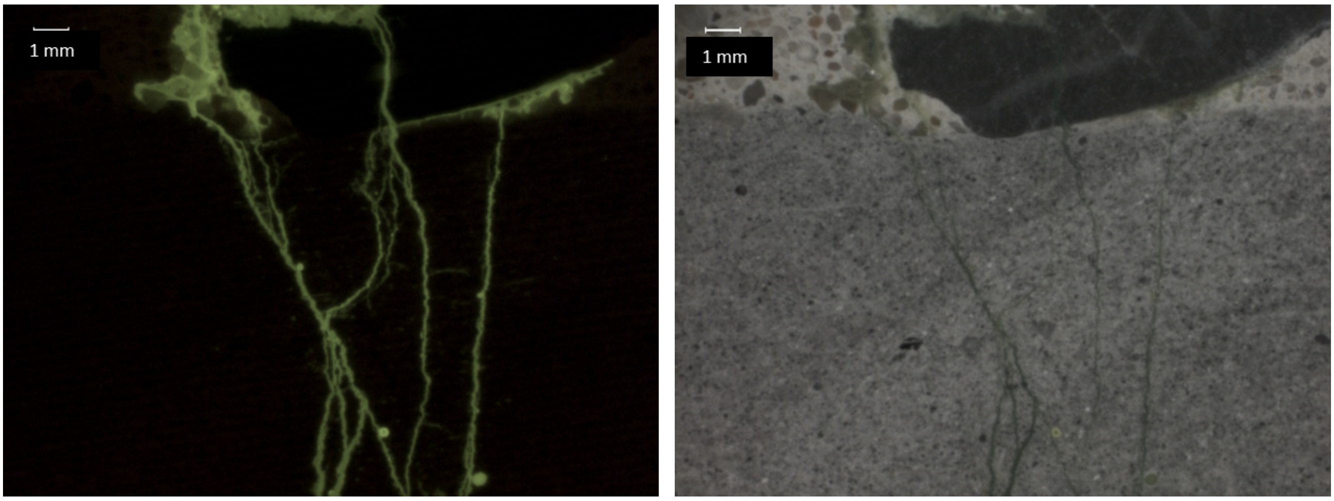

Figure 9: Final crack patterns for rough interface surface and Mix 1, impregnated with fluorescent epoxy.

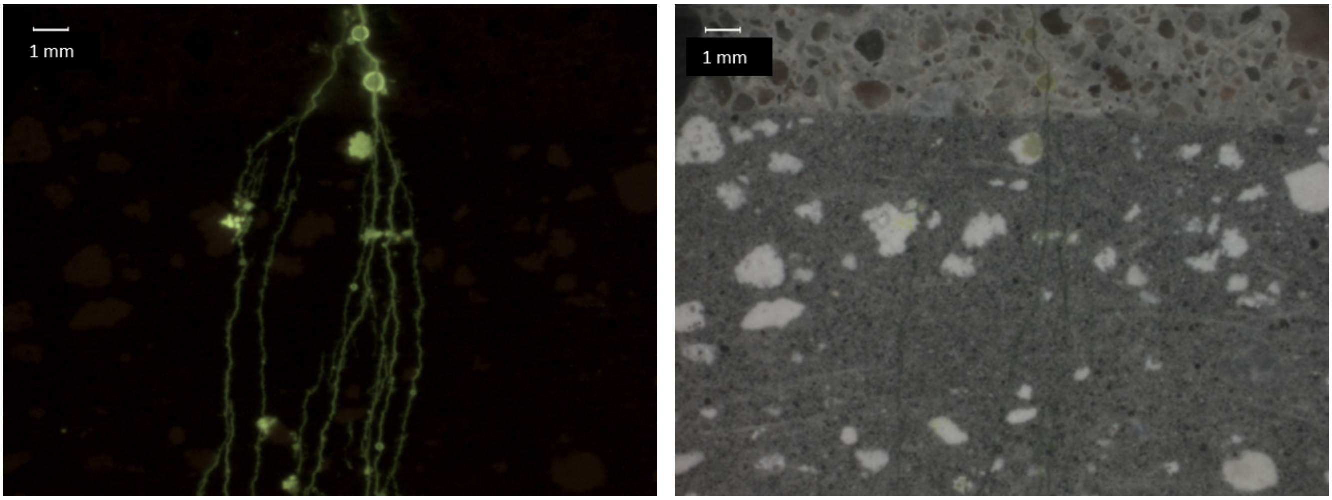

Figure 10: Final crack patterns for smooth interface surface and Mix 2, impregnated with fluorescent epoxy.

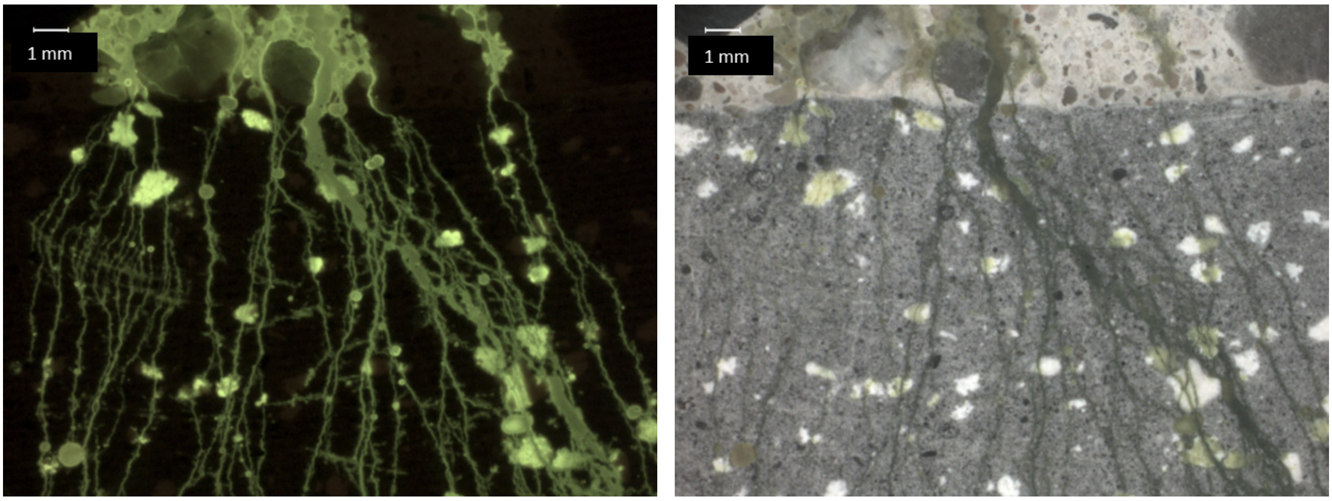

Figure 11: Final crack patterns for rough interface surface and Mix 2, impregnated with fluorescent epoxy

Restrained shrinkage

The results of the restrained shrinkage were previously reported in another paper (Sierra-Beltran et al. 2014). As can be seen in figure 12 the interface delamination height is 4.5 times higher for the control mortar (Mix 1) than for the bio-based mortar (Mix 2) after 100 days measuring. The control mix (M1) completed most of its interface delamination at early ages (90% at 14 days) compared to the delamination behaviour of the bio-based mortar (Mix 2) that continues delaminating up to 60 days. The author attributes the reduced delamination behaviour of Mix 2 to a higher creep/stress relaxation than for Mix 1. In this way, the drying shrinkage of the mortar does not result in stress and thus not in delamination.

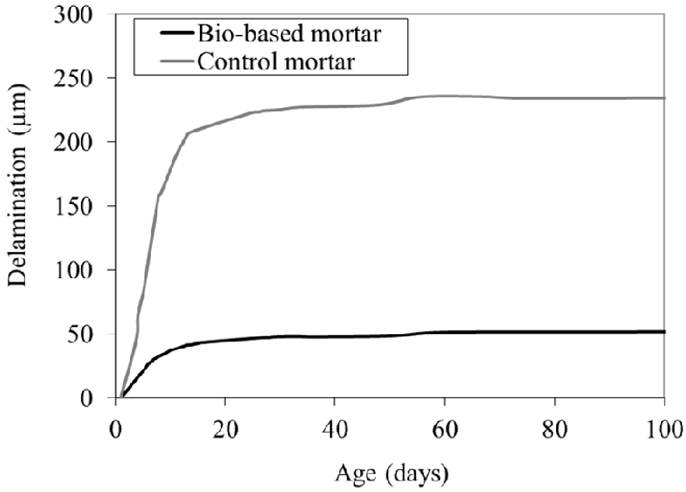

Figure 12: Specimen-end delamination heights at different ages (Sierra-Beltran et al. 2014).

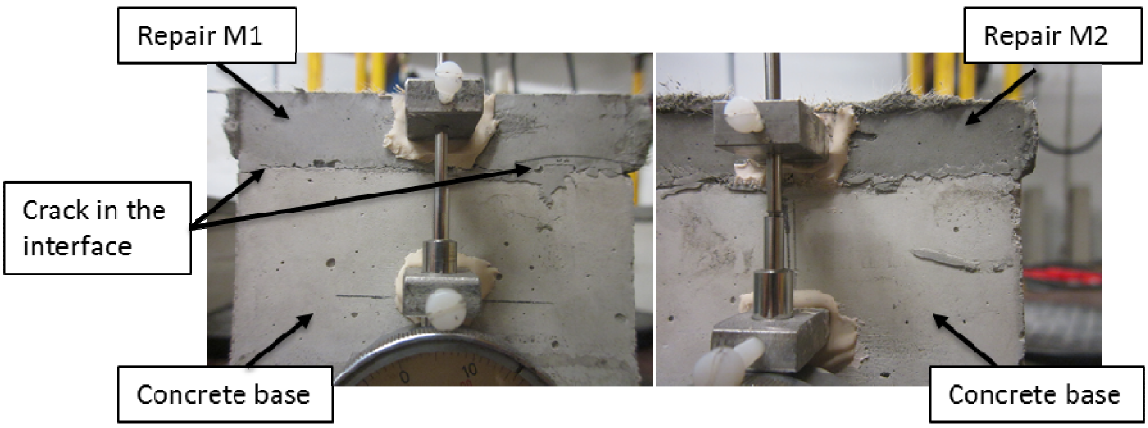

Figure 13: Specimen-end delamination at 120 days.

Durability performance

Rapid chloride migration

The average chloride penetration depths in the two repair materials in the two curing conditions are calculated by averaging the results at 7 locations in each specimen. The values of the average chloride penetration depth are given in Figure 14.

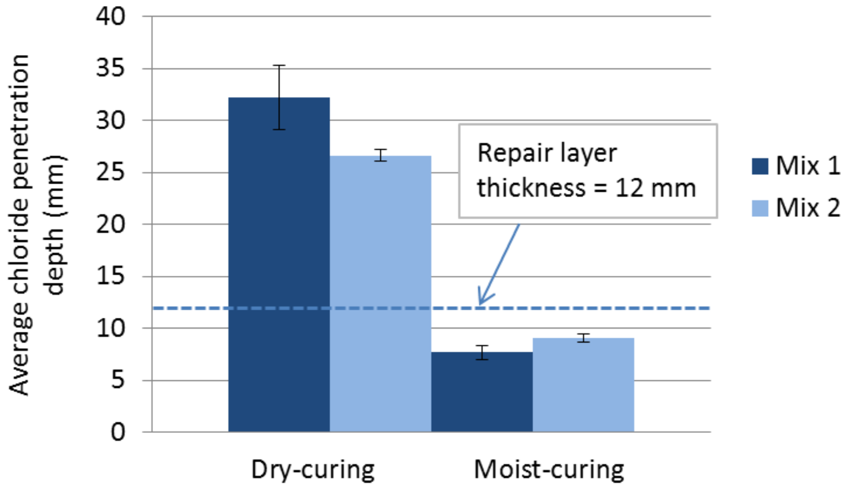

Figure 14: Average chloride penetration depths in repair materials (mm)

In the samples that were dry-cured, for both repair materials, the average chloride penetration depth is larger than the repair layer thickness (about 12 mm), which means that the chlorides penetrated into the concrete substrate. The depth for the samples with repair Mix 2 (with bacteria) is shorter than for Mix 1. The variability among samples was also shorter for samples with bacteria. This maybe due to the reduced delamination in the case of repair mortar with bacteria reported in section *"Restrained shrinkage"* compared to the delamination of repair mortars without bacteria. For the later the delamination even led to separation of the 2 layers during the drilling of the cores for these tests, with the lost of those samples.

The differences between curing conditions for both repair materials are remarkable. In the samples that were moist-cured the average chloride penetration depth, for both repair materials, is shorter than the repair layer thickness. Chloride ions penetrate into concrete through the pore system or through the cracks. In moist curing conditions the pore size distribution of the repair materials should be smaller due to the continuous hydration of cement. The repair Mix 1 has a higher content of cement than Mix 2 (as shown in Table 1). In Mix 2 the presence of LWA could also increase the overall porosity of the repair material leading to a larger penetration depth in moist-curing than for Mix 1. In order to explain the chloride transport in the repair materials the pore structure of these materials should be investigated. It is also possible that reduced shrinkage-induced stresses in the repair mortars due to the moist-curing condition will lead to a shorter chloride penetration depth for both repair materials.

The chloride penetration depth was calculated following the Nordic Standard NT BUILD 492 (1999). The results are presented in Table 3.

Table 3: Average chloride migration coefficient in repair materials (x 10^{-12} m^2/s) [standard deviation in between brackets]

Repair material	Dry-curing	Moist-curing
Mix 1	8.1 [0.8]	0.9 [0.1]
Mix 2	7.9 [0.1]	1.0 [0.1]

Thermal compatibility – Freeze and thaw cycles
The average bonding strength after freeze and thaw cycles, for both repair materials, are shown in Table 2. As can be seen in that table after the thermal compatibility tests the bonding strength decreased for both repair materials, Mix 1 in 13% and Mix 2 in 5%. Both materials fulfil the requirement for repair material of concrete structures Class R3 (≥1.5 MPa).

The average mass loss after freeze and thaw with de-icing salts for samples with Mix 1 is 0.6 kg/m^2 and for samples with Mix 2 is 0.03 kg/m^2. Both repair materials fulfil with the requirement of the standards (NEN-EN 1504-3, 2005) which indicate that the loss of mass should be less than 1.5 kg/m^2.

Based on the thermal compatibility tests results repair Mix 2 (with bacteria) can be considered more durable than repair Mix 1 since the decrease of bonding strength is lower as well as the loss of mass with de-icing salts.

CONCLUSION

Based on the experimental results and discussion, it can be concluded that both SHCC have a good performance as repair materials for concrete patch repair. Both materials fulfil the requirements of the standards for the tests done in this research and under flexural load there was no delamination between the repair layers and the concrete substrates. Nevertheless, repair material Mix 2 with bacteria has an improved behaviour compared to repair Mix 1. The interface bond strength and the flexural load are higher for Mix 1 but under flexural load Mix 2 as a repair layer behaves ductile and develops multiple cracking prior to failure. The restrained drying shrinkage was considerable lower for Mix 2. This interface delamination of Mix 1 leads to a higher chloride migration for this material. The decrease of bond strength of Mix 2 after freeze/thaw cycles and the loss of mass with de-icing salts indicated the increased durability for the repair mortar Mix 2.

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