# Self-healing of Cracks in Concrete

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# Self-healing of Cracks in Concrete

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## ABSTRACT

Repair of cracks in concrete is an important issue as cracks may endanger durability and reduce service life of reinforced concrete structures; however, large costs are generally involved if cracks are to be repaired and sometimes repair is even impossible due to inaccessibility. Therefore, in this project, we attempt to heal cracks autonomously by embedding an encapsulated healing agent into the matrix.

Water sorption measurements demonstrated there is no significant difference between the efficiency of manual and autonomous crack repair. The self-healing efficiency was also proven through visualization of the water flow by means of neutron radiography. It was shown that manually and autonomously healed cracks were water tight as no water ingress into the crack was noticed. For untreated cracks fast ingress of water was noticed along the length of the crack.

**Keywords:** Autonomous crack healing; Cementitious materials; Water sorption; Neutron radiography.

## 1 INTRODUCTION

In the case of concrete, occurrence of cracks is inevitable. Concrete can bear high compressive forces, however, the tensile strength is limited. In the tension zone, concrete will always exhibit cracks. In the initial stage, this causes no problems relating to the load bearing capacity but it does generate durability problems. Aggressive liquids and gasses may enter these cracks and they may cause concrete degradation. Therefore, cracks will grow, and subsequently, aggressive substances may reach the reinforcement and induce corrosion which may then lead to structural failure. Therefore, it is of utmost importance that concrete cracks are repaired soon after they appear. However, large costs are involved in concrete crack repair. Moreover, the indirect costs due to traffic jams and loss of productivity are estimated to be even ten times higher than the direct costs due to the repair works. As a consequence autonomous crack healing may not only lead to more durable concrete structures, but it might also lead to saving of costs.

Similar to broken bones which are able to heal autonomously and damaged skin which may self-regenerate, we want concrete to heal occurring damage by itself. Therefore, we need to re-design the material in order that the formation of damage is counteracted by a subsequent autonomous process of healing the damage. This means that the empty spaces created by cracks and defects need to be filled by new matter in order to seal the cracks, so that aggressive substances may no longer enter, and eventually mechanical properties are restored.

In order to fill the empty spaces, created by cracks, some material needs to be transferred to the location of the defect. Consequently, a mobile liquid healing agent is needed. The viscosity of the healing agent should be low, so it can easily reach the tiniest micro-cracks. Once this agent reaches the place of the defect it should preferentially expand so that a bigger crack space may be filled while only small volumes are occupied by this liquid agent before occurrence of damage. Another requisite for the healing agent is that it must form a sufficiently strong bond between the crack faces.

Furthermore, carriers are needed which contain the healing agent and which are able to sense damage and trigger the healing mechanism by releasing the healing agent. Brittle materials which are embedded inside the cementitious matrix and break whenever cracks in the matrix appear may be suitable. In addition, the encapsulation material should exhibit good adhesion to the matrix and limited extension in order to rupture upon concrete cracking.

Several types of healing agents have already been tested in research on self-healing of concrete. Mostly single-component, air-curing healing agents, such as cyanoacrylates [1-3], epoxy [4-5], silicons [2] or alkali-silica solutions [6], are preferred above multi-component healing agents, because incomplete mixing of the different components is feared. However, Dry et al. [7] stated that the potentially short shelf life of single-component healing agents might be disadvantageous. They mentioned that multi-component healing agents have more stability than single-component healing agents because they are activated at a later date, i.e. in situ. Therefore, they proposed the use of a multi-component methylmethacrylate system [7-8] and a two-component epoxy resin [2].

In most investigations hollow glass tubes are used as encapsulation material [1-3, 5-9]. In that case, the release of healing agent is activated by crack formation, which results in breakage of the embedded brittle glass tubes. The internal diameter of the tubes used ranges from 0.8 mm [1] to 4 mm [5]. Although these diameters are quite large, Joseph et al. [3] found that after crack formation only small amount of the healing agent was drawn into the crack and that most of it remained inside the tubes due to the capillary forces. Therefore, they decided that tubes with open ends would be better as this would eliminate the suction effects of the closed ends [3]. Also Mihashi et al. [6] and Dry et al. [9] made use of this technique in which continuous hollow glass tubes were embedded inside the specimens and were connected with a reservoir at the outside. Another advantage of the latter technique is that an additional amount of healing agent may be supplied when needed, so that larger cracks or a greater amount of cracks may be healed. However, as the healing agent needs to be supplied into the reservoir, this technique cannot be fully considered as self-healing.

In the research presented here, a two-component polyurethane foam was used as healing agent. Both components of the healing agent are low viscous and the polymerization reaction is not very sensitive to the mixing ratio of both compounds. In addition, this agent expands upon reaction, providing a double advantage. In the first place, the expanding reaction acts as a driving force, pushing the healing agent out of the tubular capsules upon crack formation. A second advantage of this expanding reaction is that the additional volume created by the crack may be filled up with this healing agent without leaving too many gaps behind. As the glass capsules, used in most studies, may have a negative effect on the concrete durability (alkali-silica-reaction), an alternative encapsulation material i.e. ceramics was studied in this research.

## 2 PREPARATION OF THE SPECIMENS

### 2.1 Encapsulation of the healing agent

Ceramic tubes, with an inner diameter of approximately 3 mm and a length of 75 mm, were used to carry the healing agent. A polyurethane-based two-compound healing agent was used to seal the cracks. One compound consists of a prepolymer of polyurethane and starts foaming in moist surroundings. The second compound is an accelerator which shortens the reaction time. Half of the tubes was filled with the prepolymer and the other half was filled with a mixture of accelerator and water (water + 10% accelerator). First, the tubes were sealed at one end; then, the tubes were filled with the components of the healing agent. When all tubes were filled, the other ends were sealed. Finally, two tubes filled with each of both compounds were glued together.

### 2.2 Concrete beams with(out) self-healing properties

Mortar beams were cast following the procedure described by Zhang et al. [10]. All specimens were prepared by using the mortar composition given in Table 1. Ordinary Portland cement (CEM I 52.5 N) and DIN standard sand with a maximum grain size of 2 mm were mixed with tap water according to the standard NBN EN 196-1.

Moulds with dimensions of 100 mm x 100 mm x 300 mm were used for preparation of four series of mortar beams (Table 2). All beams were reinforced with six steel bars having a diameter of 8 mm. Three steel bars were positioned at a height of 25 mm, the remaining three bars were positioned at 75 mm height (Fig. 1a).

**Table 1:** Composition of the mortar mix (W/C = 0.5)

| Material | Volume [kg/m³] |
|---|---|
| Sand 0/2 | 1530 |
| CEM I 52.5 N | 510 |
| Water | 255 |

**Table 2:** Test series used in the experiments

| Code | Description |
|---|---|
| UNCR | Uncracked beams |
| REF | Reference beams (no crack healing) |
| MAN | Manual crack healing with polyurethane |
| SHC | Self-healing of cracks with polyurethane |

When beams of the test series ‘SHC’ were made, the moulds were filled in several layers. First, a 10 mm mortar layer was brought into the moulds. When this layer was compacted by means of vibration, six couples of ceramic tubes (with one tube of each couple filled with polyurethane and the other tube filled with a mix of accelerator and water) were placed on top of it. Afterwards, the moulds were further filled with mortar until a layer of approximately 40 mm was obtained. After this layer was vibrated, again six couples of tubes were positioned onto this layer. Finally the moulds were completely filled with mortar and vibrated.

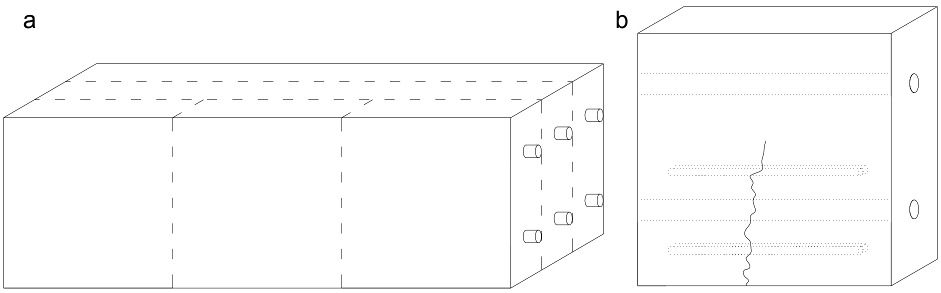


**Figure 1:** Position of the steel reinforcement and the cutting lines (a) and resulting specimen on which water sorption was measured (b)

Besides, four more test series were prepared in the same way as described above, however, samples belonging to these series contained only reinforcement bars. Beams containing to the first test series were left uncracked (UNCR), the following series was used as reference (REF), which would be cracked but from which the cracks were left untreated, the last series was used for manual healing after crack formation with polyurethane (MAN).

After preparation, all beams were placed in an air conditioned room with a temperature of 20°C and a relative humidity of more than 90%. Specimens were demoulded 24 hours later. Then, the steel reinforced prisms were cut with a diamond saw into three slices along the long axis of the prisms, as shown in Fig. 1a.

After 14 days curing the obtained slices could be loaded in three point bending in order to create cracks.

## 3 CREATION OF CRACKS

At the age of 14 days, all test series, except the series ‘UNCR’, were cracked by means of a crack width controlled three-point-bending test. The crack width was measured by means of a linear variable differential transformer with a measurement range of ± 5 mm and an accuracy of 5 µm. This LVDT was attached at the bottom of the sample and measured the transformation over a distance of 8 cm. During the bending test, mortar samples were placed onto two steel bars (diameter 40 mm) creating a span of 280 mm. The force was applied, by means of a third steel bar (diameter 16 mm), positioned in the middle of the specimen.

The crack width was increased with a velocity of 0.5 µm/sec until a crack of 400 µm was reached. At that point, the specimen was unloaded causing a decrease in crack width. The resulting crack width amounted approximately 200 µm.

## 4 CRACK HEALING

Cracks of the specimens containing encapsulated healing agent were autonomously healed. The embedded tubes broke during crack formation and both components of the healing agent were released into the crack due to capillary forces (Fig. 2a). Upon contact of both components, polyurethane foam was formed, resulting in crack healing (Fig. 2b).

For the cracks which were manually healed with polyurethane, first, the prepolymer was mixed with water and accelerator in the same proportions as encapsulated in the tubes. Next, the mixture was injected into the crack by means of a syringe with a needle. Injection was stopped when the crack was completely filled with the healing agent.

Finally, from the centre part of all specimens, slices with a width of 100 mm were sawn (Fig. 1a and b).

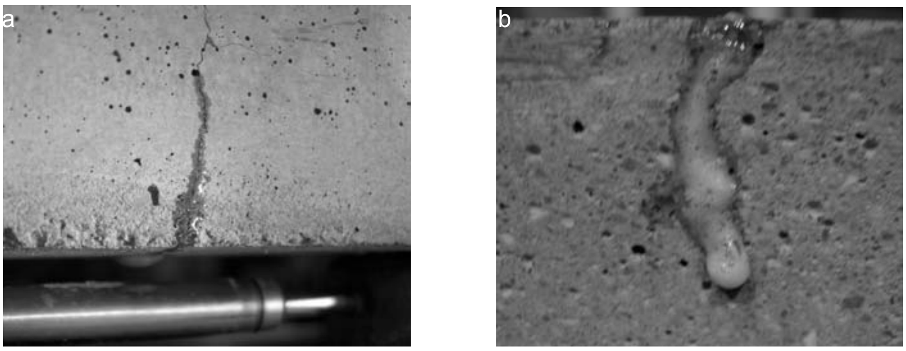


**Figure 2:** Leakage of glue out of the crack (a) and foaming of the polyurethane (b)

# 5 EVALUATION OF THE CRACK HEALING EFFICIENCY

## 5.1 Capillary water sorption

The crack healing efficiency was evaluated by capillary water sorption tests. When the specimens were 1 month old, they were placed in an oven at a temperature of 50°C. After one week, specimens were removed and the area of the surface with the crack mouth was determined. Then, the square surfaces (100 mm x 100 mm) and the two opposite small surfaces (25-30 mm x 100 mm) were covered with self-adhesive aluminium foil in order to impose unidirectional moisture movement during the test. One day later, specimens were weighed and afterwards the surface with the crack mouth was placed on two line supports in a container which was filled with water in such a way that the lower 0.5 cm of the specimens were immersed in water. At regular time intervals, specimens were taken out of the container and placed onto a non-absorptive support for one minute before they were weighed.

From these measurements the coefficient of initial water sorption ($A_i$) was determined as the slope of the linear curve fitting the measurements obtained during the first hour. The $A_i$ value measured for the reference specimens (3.950) was very high as the crack was quickly filled with water, while the uncracked specimens had much lower $A_i$ (0.902), which characterizes the undamaged cementitious material. The results showed that there is no significant difference between the efficiency of manual and autonomous crack repair (Fig. 3). The fact that the $A_i$ values obtained for the manually (1.133) and autonomously (1.312) healed samples were higher than the value measured for the undamaged material is due to the damage induced under the high tensile stress in the zone around the crack before the crack was formed. This led to the conclusion that the autonomous healed cracks were completely water tight and water uptake was due to sorption by the damaged matrix only.

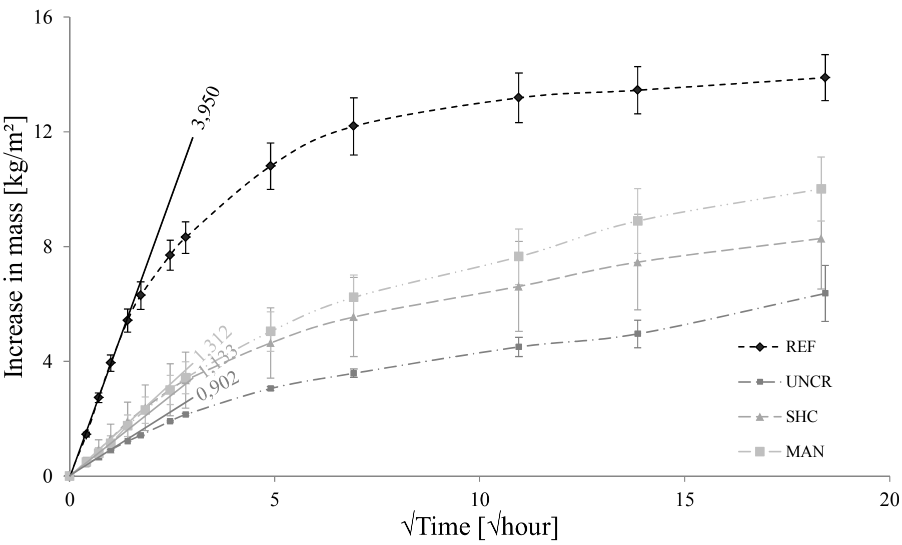


**Figure 3:** Increase in mass due to water sorption (n = 3)

## 5.2 Neutron radiography

The findings mentioned above were verified by visualization of the water migration by means of neutron radiography. These experiments were performed at the neutron beam facility of Paul Scherrer Institute (PSI) in Switzerland [11]. Similar as described above, specimens were dried and covered with a self-adhesive aluminium foil. Then, specimens were placed in a container and positioned in the neutron beam. After an image had been taken in the dry state, the container was filled with water so that the water level just touched the lower side of the samples. The kinetics of water uptake was then followed by neutron radiography.

It was shown that both manually and autonomously healed cracks were water tight as no water ingress into the cracked zone could be observed (Fig. 4). Moreover, as part of the healing agent penetrated into the damaged zone near the crack surfaces, no penetration of water into the material near the crack was noticed. For untreated cracks fast ingress of water was seen along the length of the crack. It was also proven that the interface between steel and concrete was damaged due to crack formation as water penetrated into the interface perpendicular to the crack direction. From the neutron radiographs the moisture distribution could be determined quantitatively in order to compare the different test series in detail. In the moisture profile of the reference specimen, a minimum is seen at the position of the steel reinforcement as water cannot penetrate this volume. It could be shown that neutron radiography is a very promising non-destructive test method to study the efficiency of manual and autonomous repair of cracks.

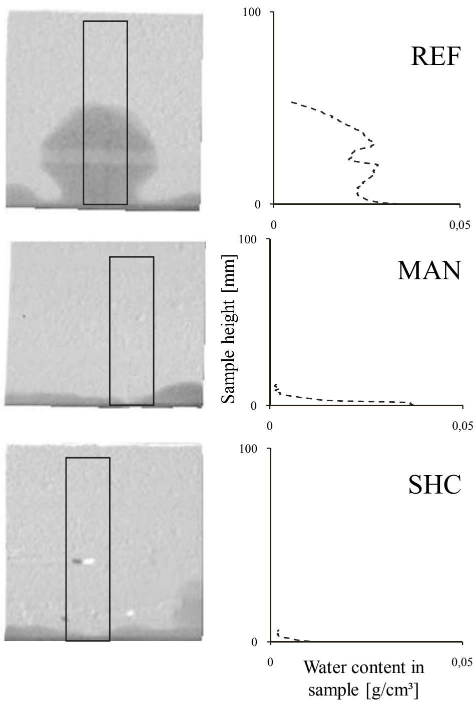


**Figure 4:** Neutron images of water penetration into cracked and healed reinforced mortar prisms after contact with water for 2h, and corresponding quantitative water profiles along a vertical axis of the sample (the crack is indicated by means of a rectangle)

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