

# Self-Healing of High-Performance Fibre-Reinforced Cementitious Composites

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Keywords: self-healing, textile reinforced concrete, super absorbent polymers

Abstract ID No : 276

## ABSTRACT

Cracks have many negative effects on the durability and mechanical properties of concrete. Preventing cracks is important for prolonging service life of concrete structures.

Self-healing of textile reinforced concrete (TRC) was investigated in this study. For this purpose, two TRC matrices were designed: the first one based on CEM I 32.5 R cement and the second one based on CEM III B 32.5 plus addition of fly ash and silica fume. The third matrix was a CEM I mixture with addition of superabsorbent polymers (SAP). Specimens were cast as rectangular plates. After demoulding, they were wrapped in plastic foil and kept in climate room for 28 days. Tensile test was chosen for controlled pre-cracking. After pre-cracking, specimens were exposed to different curing conditions of air, water and two types of wet-dry cycling regime for four weeks to simulate outdoor environment. Uniaxial tensile test, scanning electron microscopy and EDX analysis were performed in order to examine self-healing behavior of the mixes.

The tests demonstrated that – depending on the curing regime – self-healing products developing in the cracks led to some recovery of mechanical performance. Air curing did not cause any self-healing in the mixtures under investigation. CEM I-based mixtures cured in water showed the highest self-healing performance. Longer water exposure in wet-dry cycling increased mechanical performance due to self-healing. Addition of SAP supported further hydration of cement and effected positively mechanical properties in comparison to mixtures without SAP. It was proven that presence of water in cracks is the most important factor for self-healing. The healing capacity of CEM I-based TRC was the highest. It was found that newly formed self-healing products in the cracks were mostly combinations of C-S-H phases and calcites.

## 1. INTRODUCTION

Cracks may reduce the mechanical performance and shorten the service life of concrete structures. Methods for preventing cracks like self-healing, lead to increase in the durability and prolong service life of concrete. A longer service life will reduce the demand for both new structures and repair costs. Furthermore, the usage of raw

materials, environmental pollution, energy consumption and CO<sub>2</sub> production will decrease, deviously. Therefore, self-healing of concrete seems to be a promising approach economically and ecologically. Self-healing is generally defined as the ability to recover or heal the damage of materials. For concrete structures, the need in self-healing is mostly in closing cracks. The mechanisms of self-healing in concrete are usually related to further hydration of unreacted cement, swelling of concrete, formation of calcium carbonate crystals and closing of cracks by solid matter in the water (among others by fine concrete particles resulting from cracking) [1,2]. The main objective of this research is to investigate the self-healing behavior of textile reinforced concrete with two different binders: one containing CEM I 32.5 R only and one composed of CEM III 32.5 N, fly ash and silica fume. Furthermore, the effect of the addition of SAP should be studied. Textile reinforced concrete was selected since this material has well controlled fine multiple cracks under tensile loading. Specimens were pre-cracked up to a defined degree and then exposed to various curing conditions: air, water and two different types of wet-dry cycle curing. Mechanical tests as well as microscopic and porosity analysis were additionally performed to investigate self-healing mechanisms for the TRC specimens.

## **2. MATERIALS**

Natural sand and fine quartz sand were used as aggregates. The matrix composition varied by the type of binder: The first one contained CEM I 32.5 R only, while the second one was composed of CEM III/B 32.5 N, fly ash and silica fume. Biaxial textile made of carbon was used as reinforcement. The fineness of the yarns and the number of filaments per yarn were 800 and 12000, respectively. A polymer coating composed of styrene-butadiene was used to improve the bond between the textile and the surrounding finely grained concrete matrix as well as the bond between the outer and inner filaments in the yarn. SAPs made of the main monomers acrylic acid were used to investigate their effect on self-healing. SAPs were crushed fine materials produced by the bulk polymerisation technique. Naphtalin sulfonate based plasticizer was used for steering the workability of the mixtures. The water-to-binder ratio was below 0.40 in all matrices to guarantee a sufficient amount of non-hydrated binder. The specimens were rectangular TRC plates 500 mm long, 100 mm wide and 14 mm thick with 4 layers of textile reinforcement. The arrangement of the textile layers was symmetrical and parallel to the plate's surface. After demoulding specimens were wrapped in plastic foil and stored in a climate-controlled room at 20 °C until testing and further treatment. SAP materials were added to the mixture in the equal amounts of 0.3 % by mass of cement (CEM I based mixture only). However, extra water was used which increased w/c ratio by 0.06.

## **3. METHODS**

Specimens were pre-cracked by means of a deformation controlled uniaxial tension test at the age of 28 days. In order to obtain several crack characteristics and crack widths similar to those under actual service conditions, the uniaxial tensile TRC specimens were preloaded up to two different strain levels and then unloaded to the desired crack width resulting from the remaining strain. Specimens were then exposed to different curing conditions: air, water, wet-dry cycling for four weeks. Uniaxial tension tests were performed also to investigate the mechanical properties after self-healing. Microscopic analysis was conducted to view the crack conditions

before and after self-healing using environmental scanning electron microscope (ESEM).

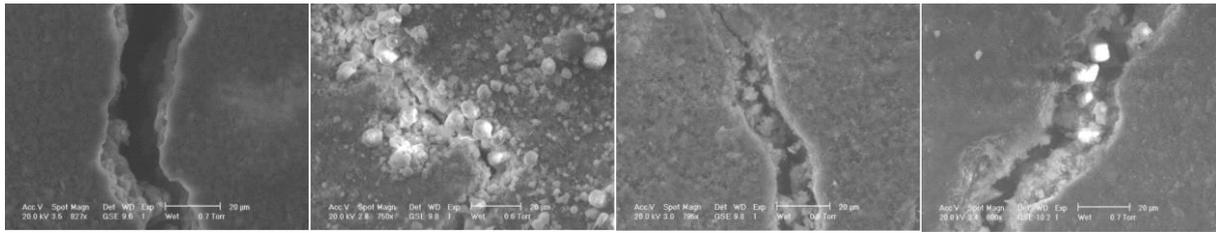
#### 4. RESULTS

The mechanical properties were compared by the first-crack stress before and after self-healing. There was no self-healing effect for air curing. The binder type did not affect the self-healing behavior in the absence of water. However, SAP addition enabled some self-healing since SAP particles could release some water for further hydration of cement particles. Specimens made of CEM I showed the most pronounced recovery after water curing. For both wet-dry cycle curing regimes, mixtures with CEM I showed the best and similar self-healing behavior. Mixtures with CEM III and pozzolanas exhibited less pronounced mechanical recovery. SAP had no clear supportive effect in these curing conditions. A longer exposure to water in wet-dry cycling enhanced the mechanical recovery rate.

Table 1: First crack stresses of the mixes exposed to different curing conditions.

	Curing Regime											
	Air Curing			Water Curing			Wet-Dry Cycle I			Wet-Dry Cycle II		
First crack stress (MPa)	CEM I	CEM III	CEM I SAP	CEM I	CEM III	CEM I SAP	CEM I	CEM III	CEM I SAP	CEM I	CEM III	CEM I SAP
Before self-healing	4.5	4.25	6.4	5.1	4.8	6.4	6.6	5.0	5.5	4.9	4.3	5.7
After self-healing	0	0	0.5	2.4	1.75	1.7	2.9	1.8	1.9	2.4	1.9	2.2
Recovery rate (%)	0	0	8	47	37	27	44	36	35	49	44	39

The SEM pictures of specimens were taken from various cracks of 20  $\mu\text{m}$  with various magnitudes and some of them were coupled with EDX analysis. The figures below are typical pictures for mixes with CEM I and exposed to various curing conditions. They are representative also for the mixes containing CEM III and pozzolanas as well as containing SAP. The air cured specimens has a crack width over 20  $\mu\text{m}$  which was the initial crack width, see Figure 1a. The edges of the crack are clear and there is no self-healing product inside the crack. The specimens cured in water for four weeks showed narrowed (below 5  $\mu\text{m}$ ) and totally closed cracks, cf. Figure 1b. Here, the crack closure capacity of the mixes containing CEM I was higher than that of other two mixes. The EDX analysis revealed that the newly produced self-healing materials were a combination of C-S-H phases and calcites. In both wet-dry cycling cured specimens, cracks were partially closed and the self-healing materials were the combination of C-S-H phases dominantly and some calcites, see Figure 1c. In addition, longer water exposure enhanced the self-healing capacity of all the mixes in wet-dry cycle curing, cf. Figure 1c,d.



a) b) c) d)  
 Figure 1: SEM pictures of the specimens containing CEM I after curing at various conditions: a) at air, b) in water, c) wet-dry cycle regime I and d) wet-dry cycle regime II.

## 5. CONCLUSIONS

Following conclusions can be drawn from the study at hand:

- Water in the crack is the most important factor for self-healing; no self-healing was observed in the experiment with air curing. Only TRC containing SAP exhibited a moderate self-healing due to desorption of some water from SAP particles.
- Self-healing products filling the cracks after water or wet-dry curing cause the recovery of mechanical performance with respect to first-crack stress. The continued hydration of unreacted cement was observed for all TRC. However, the healing capacity for mixes containing CEM I cement was the most pronounced.
- Storing in water was the most efficient curing regime with respect to self-healing of TRC. The alternate wetting and drying was less efficient, however, the efficiency increased with increasing relative duration of wetting cycles.

## ACKNOWLEDGEMENTS

This paper was based on master thesis completed at the TU Dresden under supervision of Prof. V. Mechtcherine and accepted by ITU.

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