Concrete Solutions – Grantham et al. (Eds.)
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Resistance to fatigue of self-healed concrete based on encapsulated polymer precursors

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ABSTRACT: Moving cracks are often present in concrete structures and in those circumstances any self-healing technique for concrete must satisfy specific performance requirements, to guarantee its increased durability. These requirements include the capability of withstanding multiple cycles of crack movement without failing to keep healed cracks sealed. This paper shows early results from a testing protocol suggested by the authors to assess the performance of polymers as healing materials for moving cracks. Ultrasound (US) shear waves were used for continuous monitoring of small prismatic mortar specimens containing a single healed crack under a cyclic load. The maximum amplitude of US waves transmitted across healed cracks was correlated to the area effectively healed and the magnitude of crack movement. A decreasing trend of the maximum amplitude during cyclic loading was observed for strain levels on the polymer corresponding to 70% of its strain limit, but soundness at lower strain levels was confirmed after 300 cycles.

1 INTRODUCTION

As with other emerging concrete technologies, self-healing concrete currently lacks straightforward test methods to assess its performance. This is particularly true for test methods simulating realistic conditions that are similar to those found in field structures. One such condition is the occurrence of moving cracks in concrete elements, often present in structures subjected to traffic loads or extreme daily temperature variation.

Under increasing load, self-healed cracks only remain sealed if a flexible polymer is used as healing material. Mineral materials would result in the reopening of the healed crack while a new crack would form if very stiff polymers were used. This issue has been addressed by the authors in previous publications (e.g. Feiteira et al. 2016) where the strain limit of several flexible polymers bridging moving cracks was determined. There, the strain limit was defined as the strain after which failure occurs due to rupturing of the polymer or its detachment from the crack walls, resulting in considerable increase of the water uptake through the healed crack.

If the load on a healed concrete element is cyclic, however, the strain limit of the healing material may be reduced due to fatigue. This is of great importance, but not studied to date. Even in related research areas, such as injection products for concrete repair, this topic is seldom studied, e.g. Shin et al. (2011). Regarding the research on self-healing concrete involving fatigue performance, only one study by Yang et al. (2011) was found. The differences between the two research areas are essentially limited to the fact that for injection products there is the possibility for surface preparation before introducing the liquid polymer into the crack, which is done under pressure. On self-healing concrete, the polymer precursor is released from embedded capsules immediately upon cracking of the concrete element, flowing into the crack due to capillary tension.

This paper presents early stage data of a testing setup developed to assess the fatigue resistance of a polymer precursor used as an encapsulated healing agent for self-healing concrete. The proposed test is performed at a small scale on mortar specimens and includes a continuous monitoring technique based on the transmission of ultrasound (US) waves. The use of ultrasound as a monitoring technique in this context is built upon previous results published by Malm and Große (2015). US waves are affected by changes in the propagation medium and are affected by any potential loss of continuity across the faces of healed cracks. Thus, they have been used to detect fatigue-related failure due to changes in the matrix of the polymer filling the crack or its detachment at the interface.

2 MATERIALS

A moisture-curing polyurethane precursor of low viscosity (200 mPa.s) was used in this study. From a previous study (Feiteira et al. 2016) it was known that this precursor leads to very effective sealing of cracks when used as an encapsulated healing agent and had showed also good strain capability for this application (approximately 50%). The precursor was encapsulated in Ø3 mm glass tubes cut to a 50 mm length and sealed with Poly(methyl methacrylate) glue. Although not fit for bulk addition during mixing of concrete, the brittleness and barrier properties of glass tubes make them ideal carriers for laboratory work, where they can be pre-placed into moulds and careful pouring of concrete or mortar can take place.

3 PROCEDURE

3.1 *Specimen preparation*

A pair of glass capsules was pre-placed in each mould for 40 × 40 × 150 mm^3 prisms, held by nylon wires, and mortar was poured over them. The mortar mix design consisted of cement CEM I 52.5 N, 0/4 mm sand, a cement to sand ratio of 1:3 and a water to cement ratio of 0.5. Mixing and moulding were carried out according to the procedure described in EN 196-1 and the specimens were cured in sealed conditions at 20°C for at least 14 days. After the curing period, a 7 × 150 mm^2 wide strip of fibre reinforced polymer (FRP) was glued with a structural epoxy glue along two opposing sides of the specimen (see Figure 1). The specimens were then cracked under 3-point bending, with the FRP strips at the compression side. They were then used not as conventional reinforcement, but as a way to avoid complete separation of the two halves of the specimen after cracking. A crack approximately 300 μm wide at the crack mouth remained after unloading. The final configuration of the specimens is shown in Figure 1. After a period of 3 days, to allow the healing agent to flow and harden, mortar specimens with a single healed crack were ready to be tested.

3.2 *Protocol for cyclic loading*

An LVDT was placed across the crack mouth to control the crack movement during testing. Cyclic loading occurred under bending, with each cycle defined as a crack width increase from a starting displacement of 0.05 mm to the desired maximum displacement, corresponding to a certain strain on the polymer filling the crack. After each cycle, a waiting period of 5 s was introduced at the starting displacement of 0.05 mm, so that the monitoring equipment could acquire data in stable and well defined conditions. A visual representation of these cycles is shown later in this document, in Figure 5. A loading speed of 0.013 mm/s was used, resulting in a frequency of approximately 0.07 Hz, but depending on the maximum displacement level set for the test.

3.3 *Monitoring with ultrasound transmission equipment*

A FreshCon system from Smartmote was used to generate, trigger and acquire ultrasonic pulses of 800 V and a pulse width of 5 μs. Olympus V150-RB shear wave sensors were used and monitoring took place at 2 s intervals during cyclic loading. The sensors were coupled to opposing tops of the specimens (Figure 1) with silicone gel and were kept in place with a system of small supporting metal plates and an elastic band pressing them against the specimen. The maximum amplitude of the US waves was used as the monitoring parameter.

Figure 1. Specimen configuration with a single crack at mid-span and a reinforcing FRP strip; US shear sensors are attached at opposite tops.

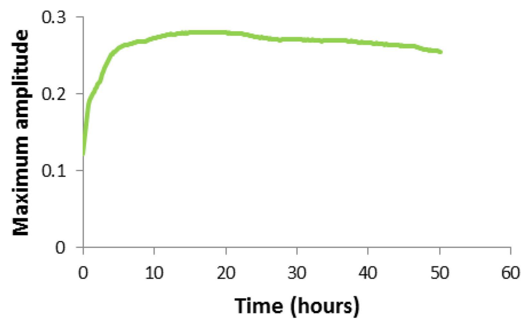

Figure 2. Increase of maximum amplitude of US wave during the healing period.

4 RESULTS

4.1 *Monitoring of the healing process*

As shear waves don't propagate well through liquid phases, the ultrasound shear waves were used to monitor the progressive dispersion and hardening of the polymer precursor inside the crack on one of the specimens, after flowing out of the ruptured glass carriers. As shown in Figure 2, while the precursor turns from a liquid compound into a solid polymer, the maximum US wave amplitude increases progressively.

Most of the hardening occurs during the first 24 h after contact with the moisture present in the mortar matrix. The slight decrease in maximum amplitude after this period could have been due to absorption of the silicone gel (used to couple the sensors) into the mortar matrix, otherwise, a slow rate of increase is expected.

The final maximum amplitude after healing is dependent on the area of the crack effectively healed. Figure 3 shows the crack faces of two split specimens

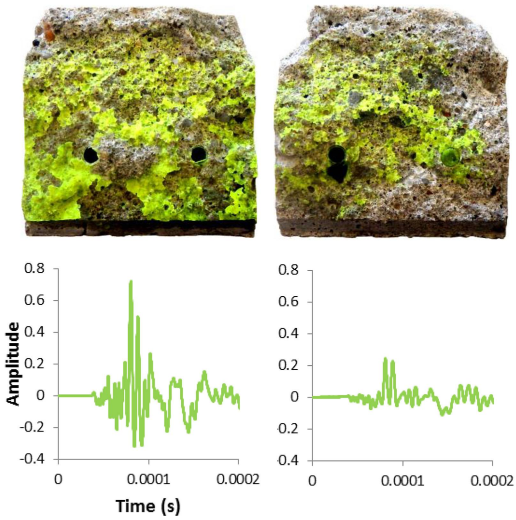

Figure 3. Crack faces of split specimens, showing a particularly well healed crack (left) and crack with a smaller area effectively healed (right); the respective waves transmitted across the cracks are shown below.

with considerably different sizes of the crack surface effectively healed. For these specimens, a fluorescent dye was added to the precursor for easy detection of the surface covered with polymer. Although there is a correlation between area healed and the maximum amplitude of the US wave transmitted across the healed crack, the amplitude is also slightly dependent on the consistency of coupling between the sensors and the specimen.

4.2 *Evolution of US wave amplitude with increasing polymer strain*

As mentioned, the transmission of ultrasonic waves is affected by changes in the continuity of the propagation medium. As a healed crack gets increasingly larger and the strain on the polymer increases, failure due to detachment or rupturing of the polymer matrix eventually occurs and a decrease of the maximum amplitude of the US wave is thus expected. This is shown in Figure 4 for several specimens.

4.3 *Fatigue assessment: combined cyclic loading and monitoring based on US wave transmission*

As US wave data was acquired constantly, at 2 s intervals, post processing of the data was required to select only the data points corresponding to the 5 s waiting period introduced in the protocol, at 0.05 mm displacement. Only this data, acquired in stable conditions, was used to monitor the continuity across crack faces. The data points of higher wave amplitude occur naturally at the moments of lower LVDT displacement, corresponding to the waiting period, as shown in Figure 5.

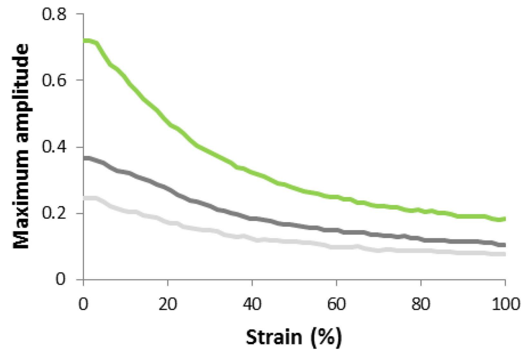

Figure 4. Progressive reduction of maximum US wave amplitude with increasing crack widening and strain on the polymer.

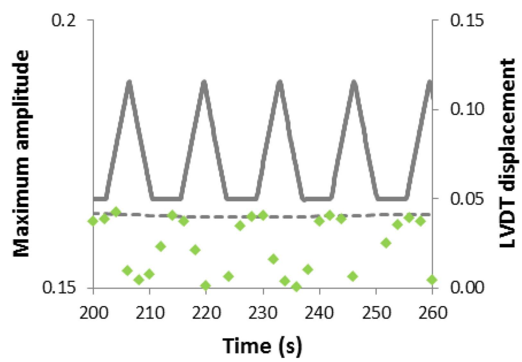

Figure 5. Approximately 5 cycles of the cyclic loading protocol showing displacement (solid line), amplitude (green) data points and upper envelope of amplitude data (dotted line).

The upper envelope of the amplitude data (line crossing data peaks) could then be used as the monitoring parameter.

Assuming the strain limit of the polymer to be 50%, after which detachment from the crack faces occurs, early tests were performed at different levels of the strain limit, i.e. 40% of the strain limit and 70% of the strain limit. The evolution of the maximum wave amplitude (upper envelope of US wave data acquired) is shown in Figure 6 for specimens at the two strain levels tested, as a function of the number of cycles performed.

For a tested strain level of 70% of the strain limit, the maximum amplitude shows a decreasing trend, suggesting that progressive failure may be occurring, which previous results show to be due to detachment of the polymer from the crack faces. For a lower strain level of 40% of the strain limit, there is no considerable change in the maximum amplitude after 300 cycles, suggesting a sound healed crack and no susceptibility to fatigue failure. A micrograph of a section of the crack mouth, where polymer could be seen at the surface (Figure 7), confirms these results and shows the polymer still attached to the crack faces.

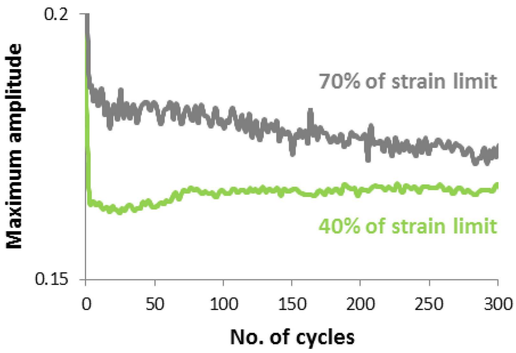

Figure 6. Evolution of maximum amplitude of US waves acquired at a stable deformation of 0.05 mm.

Figure 7. Section of 0.38 mm crack mouth where stretched polymer could still be seen attached to the crack walls after more than 300 cycles.

After these early results, the testing protocol was confirmed to be accurate and useful for monitoring the soundness of self-healing cementitious material. A larger number of tests still needs to be performed, with the inclusion of water uptake tests after a fixed number of cycles as additional confirmation of soundness or failure due to fatigue.

5 CONCLUSIONS

The maximum amplitude of US waves transmitted across healed cracks is a simple parameter that was successfully correlated with both the surface of the crack that was effectively healed with an encapsulated polymer precursor and the strain on the polymer, i.e. the amount of crack movement. Changes in maximum amplitude at stable levels of crack movement were also successfully used to monitor the soundness of healed specimens when subjected to multiple cycles of crack movement. When tested at a maximum strain level of 40% of the strain limit, after which detachment of the polymer from the crack faces is known to occur, the amplitude of the US waves was stable after 300 cycles. This suggests that at levels much below the strain limit, the self-healing technique is resistant to fatigue, which was confirmed by microscopic observation of a section of the crack mouth. At higher strain levels of 70% of the strain limit, there was however a decreasing trend of the maximum amplitude, suggesting that the strain limits of the self-healing system should be corrected to consider failure due to fatigue.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 309451 (HEALCON). The kind help of Fabian Malm (TUM) is also acknowledged.

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