Combined experimental and numerical ultrasonic assessment of self-healing within cementitious materials

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Abstract. Self-healing cementitious mixtures have been studied extensively as a solution to labour-intensive and costly manual repairs. The implementation of such materials within the construction industry requires an adequate assessment of the regained mechanical properties, ensuring a safe environment for the user. While most standardized methods are limited in their characterization potential, ultrasound allows to monitor the healing progress in a non-destructive manner and provides a direct link to the elastic properties of the member under study. Still, an assessment of the mechanical properties of the healing products is not straightforward, as the ultrasonic waves propagate not only through the healing layer, but through the intact mortar around this zone as well. To isolate the healed layer from the intact material, numerical simulations were performed. By a comparison between experimental and numerical results, the elastic modulus of the healing products deposited inside the crack was determined.

1 Introduction

The maintenance and repair of concrete structures comprises a considerable share of the construction budget worldwide. Additionally, the restoration of structures having limited accessibility remains a point of concern. As a solution, self-healing cementitious composites have been investigated, providing automated, timely repairs.

In order to assess the regained performance, various techniques have been utilized, e.g. microscopy [1], water permeability [2] and mechanical testing [3]. Whereas microscopic analysis allows to evaluate the crack closure at the surface, the method is incapable to provide information on the healing progress within the crack depth, neither on the mechanical performance of the deposited healing products. Likewise, water permeability tests assess the regain in water tightness, which is of high importance to protect any present reinforcement. Nonetheless, the mechanical capacity of the elements after healing cannot be evaluated. Therefore, mechanical (re)loading is often used to directly calculate the regained strength and/or stiffness. The drawback of such tests lies in their destructive nature, not allowing to monitor the evolution of the crack closure at distinct time intervals and impractical for in-situ use.

For this reason, the use of elastic waves has emerged as a suitable technique for self-healing evaluation. Thanks to its non-intrusive nature and sensitivity to the elastic properties of the material under study, ultrasound has shown the potential to follow-up various processes occurring within cementitious materials, going from the monitoring of the hardening process [4] and the estimation of the mechanical properties [5] to the assessment of repairs [6-8]. Concerning the latter studies, an analysis of wave parameters such as longitudinal wave velocity and attenuation enabled to distinguish between the intact, cracked and healed stages.

Still, a limitation of this method is that the results depend on the entire propagation path, which includes the cracked/healed layer as well as the uncracked mortar around this zone. As the effect of both layers cannot be separated, this means that a direct assessment of the mechanical properties of the healing products is impossible. Therefore, in an effort to isolate the healed zone from the intact material, simulations are performed [9]. By means of such numerical models, the properties of the material deposited within the crack can easily be altered to study the effect of varying density and Young’s modulus. A comparison to the experimental results then may allow to estimate the E-modulus of the healing products.

In this study, the evolution of the crack closure was monitored by using surface wave ultrasonic measurements. The mixtures studied comprised a reference PC mortar and a mortar with superabsorbent polymers (SAPs). While cementitious materials present an inherent ability to heal incurred damage through autogenous healing, the healing effectiveness is limited. The main processes that induce this type of healing are the continued hydration of unhydrated cement and the precipitation of calcium carbonate. For both of these mechanisms to occur, water is essential to be present. The inclusion of SAPs promotes the healing ability thanks to the high absorption capacity of these innovative additives [10-12]. When moisture enters the
crack, the SAPs are able to absorb and retain this moisture for a certain period of time. During dry periods, the water is released to the matrix and autogenous healing is stimulated. Besides the experiments conducted, numerical wave simulations were performed using the 2D simulation software Wave2000 Plus. Comparing the numerical results to the experimental outcome, a first estimation of the elastic properties of the healing products was achieved.

2 Materials and methodologies

2.1 Materials

Two mortar mixtures were designed, namely a reference material and a mixture with SAPs. Both blends contained a high-strength Portland cement CEM I 52.5 N from Holcim. River sand 0/2 was utilized as small aggregate in an amount of 2 to 1 with respect of the weight of cement. The water-to-cement ratio was equal to 0.35 and a superplasticizer (MasterGlenium 51, BASF) was included in an amount of 0.4% w.r.t. the weight of cement to increase the workability.

The adopted superabsorbent polymer is a copolymer of acrylamide and sodium acrylate obtained from BASF and is produced by bulk polymerization. The dry particle size is equal to 100 ± 21.5 µm. The amount of SAPs included was equal to 0.2% by weight of cement. To take account of the water uptake during mixing, an additional amount of 26 g of water per gram of SAP was included on top. In this way, an equal workability was obtained for both mixtures.

For each mixture, three mortar prisms were prepared, measuring 30 mm x 30 mm x 360 mm. A central steel reinforcement bar was added with a diameter of 6 mm and a length of 700 mm (Fig. 1.). The samples were cured for 28 days in plastic foil at 20 ± 2°C. Afterwards, multiple cracks were created by performing tensile testing. The load was increased until no new cracks appeared and a crack width between 150 µm and 200 µm was obtained.

2.2 Surface wave ultrasonic measurements

The healing progress was monitored through ultrasonic surface wave measurements. The set-up can be seen in Fig. 1 and consisted of two piezoelectric “pico” sensors, having an operating frequency between 50 kHz and 800 kHz and a peak frequency of 450 kHz. The sensors were attached to the mortar specimens by using Vaseline as a coupling agent and the distance between the sensors was maintained at 30 mm. The excitation of the wave signal was done by breaking a mechanical pencil lead. For each measurement, five pencil lead breaks were conducted. Measurements were repeated in the uncracked, cracked and various healed stages, i.e. after 3, 7, 14 and 28 days in wet-dry curing cycles.

2.3 Numerical wave simulations

The numerical simulations were performed using a commercially available software Wave2000 Plus. This software solves the 2D elastic wave equation through a method of finite differences. The simulated geometry resembles a 2D representation of the experimental set-up, which can be seen in Fig. 2. The height of the specimens was 30 mm like the experiment, while the length was 70 mm, using infinite boundary conditions to prevent any reflections occurring at the side surfaces. The receiving sensors had a size of 5 mm, corresponding to the diameter of the pico sensors. Concerning the source, a point source with size 1 mm was chosen to simulate the breaking of a thin pencil lead featuring one cycle of 450 kHz. The spatial resolution of the shown geometry was equal to 0.05 mm.

The material properties utilized for the numerical model equal the properties of the reference mortar. The bulk density was equal to 2170 kg/m³ and the E-modulus and Poisson’s ratio were set at 27.9 GPa and 0.3 respectively, based on experimental data. Concerning the steel reinforcement, a density of 7850 kg/m³ was taken, together with a Young’s modulus of 210 GPa and a Poisson’s ratio of 0.3. The crack was simulated by creating an air gap above and below the steel reinforcement bar, so that an intact reinforcement was maintained. The width of the crack was equal to 200 µm and the crack was centred with respect to the receivers. The density of air was equal to 1.2 kg/m³ and the longitudinal wave velocity was equal to 330 m/s.

Fig. 1. View of the tensile specimens and placement of the ultrasonic sensors.

After cracking, the specimens were placed in wet-dry curing cycles to promote the healing ability. The cycles consisted of 23 hours in dry conditions at 20 ± 2°C and 65 ± 5% RH and 1 hour submersion in water at 20 ± 2°C.
3 Results and discussion

3.1 Surface wave ultrasonic measurements

In Fig. 3, the evolution of the received waveforms of a representative reference specimen is shown. The signal received by the first, closest sensor is nearly identical for all experiments conducted, as the wave arrives at this sensor before travelling through the crack. In the uncracked state, it was seen that the wave received by the second sensor exhibits a lower amplitude due to the attenuative effect of the material. Also, the arrival time of the wave comes after the arrival at the first sensor, due to the longer travel path. By calculating the time difference between the arrival at both sensors, the longitudinal wave velocity can be calculated by dividing the distance between the two receivers (0.03 m) by the travel time of 6.5 µs, leading to a velocity of approximately 4647 m/s.

![Fig. 3. Evolution of received waveforms during healing.](image)

After cracking, the arrival of the sent signal at the second receiver was strongly delayed, due to the discontinuity within the travel path. The travel time was now equal to 11.8 µs, meaning that the longitudinal wave velocity lowered to approximately 2534 m/s.

For further analysis of the self-healing evolution, the longitudinal wave velocity was calculated for every ultrasonic measurement conducted and an average value was reported per mixture composition and per measuring day. The results are shown in Fig. 4. The exact values and the standard deviation on the average are detailed in Table 1. At day zero, two velocity values per mixture are obtained, namely one for uncracked state and one for the cracked situation. In the uncracked state, relatively high values are received. Due to the additional porosity present inside the SAP mortar, the velocity measured within these blends is slightly lower compared to the reference material.

![Fig. 4. Longitudinal wave velocity vs. time of reference and SAP mortars.](image)

<table>
<thead>
<tr>
<th>Table 1. Summary of wave velocity and restoration of reference and SAP mortars with their respective standard deviation.</th>
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<tr>
<td>Wave velocity (m/s)</td>
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<td></td>
</tr>
<tr>
<td>Ref.</td>
</tr>
<tr>
<td>Uncracked</td>
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<tr>
<td>Cracked</td>
</tr>
<tr>
<td>3 days</td>
</tr>
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<td>7 days</td>
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<td>14 days</td>
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<td>28 days</td>
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After cracking, the velocity reduced significantly for both mixtures, signifying the air gap within the travel path. The specimens were then placed in wet-dry curing cycles in order to promote the healing process. Over time, both materials showed an improvement of the wave velocity, suggesting crack closure.

To obtain a more appropriate comparison between both materials, the restoration of the velocity over time was calculated by the difference between the healed and cracked velocity values, divided by the difference between the uncracked and the cracked velocity values. In this way, velocity variations due to different porosity and crack size and geometry are omitted. Fig. 5 summarizes the restoration percentage obtained for the reference and SAP mixtures. The exact values and the standard deviation can be found in Table 1. From these results, it was observed that the reference mortar showed a strong restoration during the first week of curing, whereafter the evolution of the crack healing remained limited. In case of the SAP mixture, a high increase in velocity was noticed during the first three days of wet-dry curing, while afterwards the process slowed down. Still, a higher recovery was noticed compared to the reference blend, indicating the promotion of self-healing through the presence of superabsorbent polymers.
3.2 Numerical simulations

Using Wave2000 Plus, a simulation of the uncracked and cracked experimental result was conducted and is shown in Fig. 6. Similar to the surface wave experiments, the arrival of the wave in the second, further sensor is delayed with respect to the arrival at the first sensor. A longitudinal wave velocity equal to 4615 m/s was obtained. In the cracked state, the travel time increased even more, due to the air gap present between the two receivers. In this case, the wave velocity was equal to 3845 m/s.

After inserting the air gap, various healing situations were simulated to be compared to the experimental results. Two main cases were simulated, being a partially healed crack and a completely healed crack. In case of partial healing, the air gap was filled on the top and bottom 3 mm, resembling the increased deposition closer to the outer surfaces as reported in literature [13]. For a completely healed crack, the entire air gap was filled with healing material. To simulate the healing progress, the material inside the crack was systematically varied, going from air to pure CaCO₃ crystals, which are abundantly formed during autogenous healing. In between these two materials, the E-modulus of the filling material was changed, namely 0.01 GPa, 0.1 GPa, 1 GPa, 10 GPa and 70 GPa, the latter being the value for pure CaCO₃. Besides these varying Young’s moduli, two density values were adopted, being the density of CaCO₃ equal to 2711 kg/m³ and a value of 1600 kg/m³, which is considerably smaller than the mortar’s density.

From all simulated cases, the longitudinal wave velocity was calculated. The results for both densities in case of a completely healed crack are depicted in Fig. 7. It was noticed that the effect of the density variation was negligible, i.e. within 1% of difference, while the variation of the E-modulus strongly influenced the wave velocity. Increasing the E-modulus increased the longitudinal wave velocity obtained, as expected. Within the range of 0.01 GPa and 1 GPa, the increment in velocity was the highest, whereas further rises of the E-modulus had a more limited effect.

Since the effect of density was negligible, it was chosen to further compare the results of partial and complete healing using a density of 2711 kg/m³. Fig. 8 depicts the evolution of the wave velocity for both simulated healing cases. It can be observed that the evolution for the partially healed crack follows a similar trend, however, the velocity values obtained are systematically lower compared to the complete healing situation. Still, the difference in velocity between both healing cases is small, i.e. about 3%. This can be explained by the fact that the top layer already allows for the Rayleigh wave to pass to the further sensor, which contains most of the energy.

The above results confirm the sensitivity of numerical wave simulations to the elastic modulus of the filling material. A comparison between the numerical outcome and the experimental results would therefore prove useful to estimate the E-modulus of the formed healing products. The restoration percentages in terms of wave velocity was calculated for the density of 2711 kg/m³ in both simulated healing cases, similar to the experimental results, and are shown in Fig. 9.
Young's moduli, two density values
0.01 GPa, 0.1 GPa, 1 GPa, 10 GPa and 70 GPa, the latter
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autogenous healing.

crystals, which are abundantly formed during
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closer to the outer surfaces as reported in literature
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and cracked experimental result was
Using Wave2000
Fig
6

After inserting the
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5

Evolution of received waveforms in Wave2000 Plus.
The above results confirm the sensitivity of
healing products.
It was noticed that the effect of the density variation was
explained by the fact that the top layer already allows

Within the experimental results, a restoration of
between 40% and 45% was reached for the reference
and SAP mortars after 28 days of wet-dry curing. When
comparing these values to the numerical results, a
restoration of about 45% corresponds to a modulus of
close to 1 GPa (see Fig. 9) for both healing cases. This
outcome suggests a relatively low stiffness of the
deposited material, which would be expected in case of
the pursued healing conditions. The autogenous healing
process is highly dependent on the presence of moisture,
unhydrated cement and Ca(OH)₂. In case of absence or
consummation of these components; autogenous
healing will no longer take place. Additionally, the
 cracking created during the experiments are through-going
cracks. The only connection between both crack walls is
due to the steel reinforcement bar. For this reason, the
number of precipitation surfaces is relatively limited. In
general, ultrasound is capable of qualitatively,
indicating the healing, well combination with numerical
simulations, sheds light in the practical question of the
stiffness of the healing material.

4 Conclusions

This study comprised a combined experimental and
numerical assessment of the self-healing process within
cementitious materials. Concerning the experiments
conducted, two mortar blends were considered, i.e. one
reference material and one with superabsorbent
polymers. To promote the healing ability, wet-dry
curing cycles were applied for 28 days. The results of
the ultrasonic surface wave measurements indicated the
closure of cracks over time through the improvement of
the longitudinal wave velocity, which was significantly
decreased upon cracking. Additionally, the mixture with
SAPs showed an increased recovery of the longitudinal
wave velocity, indicating the promotion of autogenous
healing.

Besides the experimental series performed,
numerical wave simulations were conducted to validate
the sensitivity of ultrasound to the deposition of healing
products within the crack. While the density of
the healing layer had only a negligible effect on the results,
the variation of the E-modulus strongly affected the
obtained wave velocity. Between 0.01 GPa and 1 GPa,
the velocity increased steeply, whereafter a more limited
improvement in velocity was seen for increasing
stiffnesses up to 70 GPa. These results show the
excellent sensitivity of ultrasonic waves to slight
changes in the stiffness development and thus its
potential to evaluate the self-healing process within
cementitious materials.

Through a comparison between experiments and
simulations, the E-modulus of the formed healing
products was estimated between 0.1 GPa and 1 GPa.
Whereas the outcome of this study proves the ability of
a combined experimental-numerical investigation to
calculate the elastic properties of deposited self-healing
material, it should be noted that the simulations were
performed using a 2D numerical software. Therefore,
the model does not include the actual 3D spreading of
the wave beam. A simulation using a 3D software would
therefore prove useful, while different frequencies could
prove useful for different sizes of cracks and filling
percentages.

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