Self-healing evaluation through ultrasonic measurements and 3D numerical simulations

Nobuhiro Okude1*, Gerlinde Lefever2, and Tomoki Shiotani1
1 Department of Civil & Earth Resources Engineering, Graduate School of Engineering, Kyoto University, Katsura Campus, Nishikyo, Kyoto, Japan
2 Department of Mechanics of Materials and Constructions, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

Abstract. Self-healing cementitious materials have gained attention as a resolution to costly and labour-intensive manual repairs. Up to now, the regain in mechanical properties after healing is mostly evaluated through destructive tests, which are neither applicable for in-situ measurements, nor allow to monitor the healing evolution. Thus, a non-intrusive measuring technique is in demand, which could be found in the application of ultrasonic measurements (elastic waves in the ultrasonic frequency range). In this study, a method for evaluating mechanical recovery after healing is investigated by means of elastic waves. It comprises an assessment of the healing ability of mortars by experiments and numerical analysis. Experimental results show the decrease in wave velocities and amplitudes due to the presence of cracks, while upon healing both values are partially restored. To isolate the healing layer from the intact mortar around it, 3D numerical simulations are performed. A comparison between experimental and numerical results enables the determination of elastic moduli of the healing products filled in cracks. Further, a method to evaluate the stiffness and the filling ratio of healed layers at the crack is proposed, based on characteristics of elastic waves (wave velocity and amplitude).

1 Introduction

Concrete is known as one of the most used construction components worldwide. Whereas the main constituents have remained similar over time, the mixture design is evolved significantly to accommodate the contemporary needs for stronger and more durable construction materials. These modifications up to the microstructural level require in their turn an adaptation of the measuring methods to allow an assessment of the properties of such novel materials.

Over the past decades, non-destructive use of elastic waves has shown its potential to evaluate various characteristics of cementitious materials, due to its sensitivity to the elastic properties of the material under study. More specifically, ultrasonic measurements (the use of elastic waves in the ultrasonic frequency range) have been used extensively to determine the setting time [1], to estimate the mechanical performance [2] and to identify existing damage [3-4]. Closely related to the latter topic is the evaluation of the repair effectiveness, linked to manual repairs [5] as well as self-healing [6-7].

Through an analysis of such wave parameters as wave velocity and attenuation, a distinction between the intact, cracked and healed stages is to be applicable. This is because the velocity readily decreases upon cracking, while the closure of cracks shows a partial restoration. These findings could lead to the evaluation of self-healing effectiveness.

Nevertheless, a limitation of this technique lies in the fact that the wave parameters are characteristic for the entire propagation path, which not only includes the cracked/healed layer, but also the intact cementitious matrix around. In this concern, an estimation of the mechanical properties of filled in healing products is crucial to assess whether a stiff connection is formed between the crack surfaces, which would result in regained mechanical performance. To isolate the healing layer from the uncracked matrix, numerical simulations were attempted to clarify the elastic properties of the healed layer and its effect on the wave propagation [8]. Although some trends were confirmed by simulation analysis, the results showed some deviations. One of reasons could result from the use of a 2D simulation software, which is limited to analysis of a plane geometry instead of a 3D model. Therefore, in an attempt to increase the accuracy of the numerical simulations, a 3D software is utilized in the present investigation.

Within this research topics, various cementitious mixtures have been investigated. These materials could present an inherent ability to repair damage through autogenous healing, because the healing effectiveness is to be promoted through filling additives. Here, superabsorbent polymers (SAPs) and nano silica are selected. SAPs promote the autogenous healing through the gradual release of absorbed water from the environment [9], as moisture is essential for subsequent hydration and calcium carbonate precipitation. On the
other hand, nano silica improves the healing ability through a pozzolanic reaction with Ca(OH)₂ [10]. Besides experiments conducted, 3D numerical simulations are performed to assess the elastic properties of the healing products filled in the cracks for a comparison between experimental and numerical results.

2 Experiments

2.1 Materials and specimens

Four mixtures of mortar were tested, which are a reference mortar, that with SAPs, that with nano silica and a blend combining both additives (see Table 1). Cement used is Portland cement (CEM I 52.5 N Strong). As fine aggregate, river sand (smaller than 2 mm) was used with the ratio of 2 to 1 of the weight of the binder. The water-to-binder ratio was kept constant at 0.35 for all mixtures and a superplasticizer (MasterGlenium 51, BASF) was added in an amount of 0.4% to the binder weight to increase the workability. Since nano silica acts as a binder, cement was replaced partially by nano-silica in the concerned mixtures to maintain the binder quantity. In case of the superabsorbent polymers, SAPs were simply added to the binder amount, because they are chemically inert in mixtures.

The type of superabsorbent polymer used is a copolymer of acrylamide and sodium acrylate (BASF) and is produced by bulk polymerization. The amount of SAP added was equal to 0.2% by weight of the binder and an additional amount of water equal to 26 g per gram of SAP was included to maintain the workability. The nano silica used is a colloidal silica (LUDOX® HS40, Grace). The nano silica was replaced with 2 weight% of the binder.

Table 1. Mortar mixtures tested

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Mortar</th>
<th>SAP</th>
<th>HS40</th>
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<td>Ref.</td>
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For every mixture, three mortar specimens with dimensions of 30 mm × 30 mm × 360 mm were cast. A reinforcing steel bar with diameter 6 mm and length 700 mm is arranged at the center of axial direction in the specimens (see Fig. 1 left). In addition, a central line was drawn onto the surface, which was used for the positioning of the sensors during the healing assessment. The specimens were cured in plastic foil for 28 days at 20 ± 2 °C. Afterwards, cracks were nucleated by means of a tensile test, using a testing system with a capacity of 100 kN (see Fig. 1 right). As shown, a tensile load is applied by the use of clamped steel jig at a speed of 0.01 mm/s. Due to the elongation of the steel bar, the specimen showed multiple cracks laterally and on average six cracks were formed.

The tensile load was increased until no new cracks generated and eventually the average crack widths between 100 µm and 200 µm were observed after unloading. To promote the crack healing mechanism, the specimens were placed in wet-dry curing cycles for 28 days. These cycles consisted of 1 hour submersion in water at 20 ± 2 °C and 23 hours of dry conditions at 20 ± 2 °C and 65 ± 5% RH. The steel bars protruded from mortar were wrapped with parafilm to avoid any corrosions.

2.2 Ultrasonic surface-wave measurements

Ultrasonic surface wave measurements were conducted to monitor the progress of self-healing. Two piezoelectric sensors are placed on the surface of the specimen, at the position of the center line, using a thin layer of vacuum grease as a coupling agent as shown in Fig. 2.

The sensors used are broadband “pico” sensors, having an operating frequency between 50 and 800 kHz. The resonant frequency of these sensors is about 450 kHz. A single measurement was conducted by breaking of a thin pencil-lead to excite an elastic wave. Every measurement was repeated five times, alternating the position of the pencil; i.e. closer to the left or right sensor. A schematical representation of the test method is illustrated in Fig. 2.

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The measurement for one specimen was repeated, before cracking, right after cracked and at 3, 7, 14 and 28 days after, under the wet-dry curing cycles. In the uncracked state, the sensors were simply placed onto the center line to characterize the intact microstructure. After cracked, one to two separated cracks were chosen to be tested. Specific cracks were taken in order to eliminate any interaction of nearby cracks on the
ultrasonic measurements, which could provide immediate reflection of the emitted waves. For these measurements, the sensors were still placed along the center line, having the crack in between them.

To eliminate the influence of saturation of water in the specimen, the tests were performed at the same moment within the curing cycles, as being 16 hours after the submersion in water.

3 Three-dimensional (3D) analysis of elastic-wave propagation

3D analysis of elastic-wave propagation was conducted with a software (Wave3000, Cyberlogic), which solves Eq. 1 by the finite difference method (FDM).

\[
\rho \frac{\partial^2 w}{\partial t^2} = \left[ \mu + \eta \frac{\partial}{\partial t} \right] \nabla^2 w + \left[ \lambda + \mu + \phi \frac{\partial}{\partial t} + \frac{\eta}{3} \frac{\partial}{\partial t} \right] \nabla (\nabla \cdot w), \quad (1)
\]

where \( \rho \) is the density of mortar, \( \lambda \) and \( \mu \) are Lame constants, and \( \eta \) and \( \phi \) are viscosity coefficient of shear and bulk, respectively. \( t \) is the time and \( w \) is the surface displacement.

3.1 Simulation model for experiment

A 3D simulation model for the experiment is shown in Fig. 3. The length of the specimen in the experiment was 360 mm, while the model has 70 mm length in the axial direction. The crack of 0.2 mm width is located at the center of the specimen in the X-direction. Boundary conditions are assigned with air layer in the Y- and Z-directions, while an infinitely long boundary with mortar and rebar is assumed in the X-direction. Two sensors of 5 mm diameter are placed 15 mm from the center crack. A driving sensor replicates a pencil lead break and thus is assumed as 1 mm diameter. The diameter of the rebar is 6 mm and cracks are modelled in mortar, as no cracks are taken into account in the rebar. A spatial mesh-size is set to 0.05 mm and a simulation period is 50 \( \mu \) s. The specific density of mortar is 2170 kg/m\(^3\), its modulus of elasticity is 27. 9 GPa, and Poisson’s ratio is 0.3. The density of rebar is 7850 kg/m\(^3\), its modulus of elasticity is 210 GPa, and Poisson’s ratio is 0.3.

Concerning damping coefficients for the mortar, an attenuation value of 0.32 dB/mm was obtained, after matching the experimental results. The density of air was 1.2 kg/m\(^3\) and its longitudinal wave velocity was set to 330 m/s. In order to imitate the process of self-healing, the elastic moduli of the healing material were varied, as 0.01 GPa, 0.1 GPa, 1 GPa, 10 GPa and 70 GPa, while the density was fixed as 1600 kg/m\(^3\) in all the cases. According to the previous research, the effect of the density on the wave propagation is significantly smaller than the stiffness \[8\]. As seen in Fig. 3, reflections are to be observed at the boundaries of the model. Consequently, another model without reinforcement is prepared as shown in Fig. 4. Except for the top surface with air layer, other boundaries are assumed as infinitely long as no reflections are generated. Other conditions and material properties are the same as those in Fig. 3.

In these models, the force with one-cycle sine wave of 450 kHz was driven at the source, and elastic waves were detected at receiving sensors located at Ch. 1 and Ch. 2. Targets of the analysis were velocities and amplitudes of the longitudinal waves due to variations of the stiffness (i.e. the modulus of elasticity).

3.2 Effect of filling ratio of healing materials

In the case where the healing materials are filling the crack, the effect on elastic wave propagation is to be varied, depending on the filling ratios. Consequently, the effect is analysed by employing the infinite model without reinforcement in Fig. 4.

As shown in Fig. 5, filling areas inside the crack are varied as 5\%, 10\%, 20\%, and 50 \%. In the figure, blue lines depict filling layers, while blank areas correspond to air. The line widths are given with 0.15 mm for 5\%, 0. 3 mm for 10\%, 0.6 mm for 20\% and 1.5 mm for 50 \%, respectively. Driving force is of one-cycle sine wave, similar to other simulations.

Fig. 5. Analytical models for filling areas in the crack.
4 Results and discussion

4.1 Experimental results

In Fig. 6, two waveforms received during the ultrasonic measurement on a reference specimen are shown. The arrivals of the waves at a closest sensor (Ch. 1) and a furthest sensor (Ch. 2) are marked by the orange arrows. As well known, the arrival at the further sensor is delayed, due to the increased travel path. The time difference between the arrivals at both sensors is called the travel time and allows to calculate the longitudinal wave velocity by dividing the distance between the sensors by this time difference. Here, the threshold level for triggering was set to 10 times larger than environmental noise. Thus, the travel time was estimated between two triggered times over the threshold level.

The amplitude of the wave signals is referred to as the highest voltage received as illustrated in Fig. 6. The decrease in the amplitude of Ch. 2 sensor was observed with respect to Ch. 1, as the attenuative effect of the material. From these amplitudes, the attenuation can be calculated by Eq. 2.

\[
\text{Attenuation} \left[dB/mm\right] = \frac{1}{30mm} \times 20 \times \log\left(\frac{A_{\text{furthest}}}{A_{\text{closest}}}\right)
\]

From all measurements conducted, the average longitudinal wave velocity and attenuation are determined per mixture series in Table 1. The evolutions on the velocity of the longitudinal waves are presented in Fig. 7. Two measurements per mixture composition were performed, being one in the uncracked state and one in cracked conditions. At the beginning (day zero), in case of the intact material of the uncracked state, velocities are obtained between 4300 and 4700 m/s. The mortar mixtures with SAPs (A and C) show slightly lower velocities compared to the reference and nano silica blends, due to the increased macroscopic porosity.

After cracked the velocity is drastically reduced, as the discontinuity prohibits the wave signal to follow the shortest path between both sensors. Afterwards, as wet-dry curing is applied, the wave velocity increases again, showing a partial restoration compared to the original velocity value. While evident recoveries are noticed for all mixtures, mixture C demonstrated the more continuous improvement over the entire healing period, due to the combined effect of SAPs and nano silica. Fig. 8 depicts the development of the attenuation over time. Initially, relatively low attenuation values are obtained, while mortars including SAPs (A and C) show higher attenuation due to the increased porosity. The discontinuity induced with the cracks strongly increased the attenuation, from approximately 0.3 dB/mm to almost 1 dB/mm. In a similar manner to the wave velocity, the application of wet-dry curing cycles partially restored the attenuation. The mortar with SAPs and nano silica again show the more continuous restoration with respect to the other mixtures. These results confirm the excellent potential of ultrasonic measurement to follow-up the self-healing process in cementitious mixtures.

4.2 Effect of the stiffness of the healing layer

Visual results of wave propagation in the model are given in Fig. 9. The effect of the healing layer is clearly observed. The cases that the modulus of healing layer is 0.01 GPa (Fig. 9 (a)) and is 10 GPa (Fig. 9 (b)) are illustrated. The wave fields at 7 μs elapsed after impact are shown at the top, while those at 15 μs elapsed are shown at the bottom. A grey scale indicates resultant displacements of X-and Y-directions at Z = 17 mm. The right side of each figure shows a cross section of mortar at X = 35.2 mm (15.2 mm away from Ch. 1 and 14.8 mm away from Ch. 2). The thickness of the healing layer is 0.2 mm. As can be seen, almost all waves are reflected at the crack in the case of 0.01 GPa, while a part of waves was transmitted through the crack in the case of 10 GPa. Relations between the wave velocities and elastic moduli are shown in Fig. 10. Here, results of the
two models in Figs. 3 and 4 are given. It is observed that the effect of reflections is minor, and the velocity increases with the increase in the stiffness. The velocity increase is dominant in the case of low moduli, as the velocity increases approximately 20% with the increase in the moduli from 0.01 GPa to 1 GPa. In contrast, the effect of the increase from 10 GPa to 70 GPa is negligible.

According to experimental results, the wave velocities are around 2500 ~ 3800 m/s after cracking/healing. However, results of the simulation analysis show velocities around 3800 ~ 4700 m/s, which are fairly high and were previously observed in 2D simulation analysis [8]. The fact could result from the effect of threshold level in the experiments. The waves from the simulation analysis contain no noise, whereas the experimental threshold was set to 1.1 times the environmental noises. As a result, the arrival times are delayed compared to the precise arrival, in particular, such a false reading could occur in the case of low-amplitude waves.

Then, results of the attenuation are studied. The relation is given in Fig. 11, where both cases of reflected (experiment) and unreflected boundaries are shown. It is found that the attenuations in the experimental model are lower than those of the non-reflected model. This is because the attenuations become low due to reflections inside the specimen, while the attenuation in the unreflected model becomes high without the effect of reflection. As seen in Fig. 10, the effect of reflection is little observed with respect to the longitudinal wave velocity, whereas the attenuation presents clearly the effect of reflection. Thus, the attenuation is affected by size and shape of the specimen.

The effect of the moduli of the healing layer is realized, as the attenuation decreases with an increase in the stiffness. Further, the effect of the stiffness increase is emphasized at the stage of low stiffness, as found in the velocity.

Now, simulation results are to be compared with those of experiments. Following 28-day curing, attenuation around 0.8 is obtained in the experiment of the case A (mixture with SAP). In contrast, an attenuation around 0.6 is observed in the case C (mixture of SAP and HS40). According to simulated results between attenuation and the E-moduli, the stiffness of mixture C results in 0.01 GPa, while that of mixture C corresponds to 0.5 GPa. Thus, the difference of the moduli could result from the effect of HS40.

Concerning the factors that affect elastic wave propagations, the effect of filling ratios was considered. The results of simulation analysis for two E-moduli in the model of Fig. 4 are given in Figs. 12 and 13, for longitudinal wave velocity and attenuation respectively. The unreflected model was adopted to isolate the effect of the filling ratios. The relation between the filling ratios and the wave velocities is shown in Fig. 12. The cases of 10 GPa and 0.01 GPa are compared. With the increase in the ratio from 5% to 100%, the velocities shift from 4400 m/s to 4600 m/s (approximately 4%) in the case of 10 GPa, and from 3500 m/s to 3800 m/s (approximately 8%). This implies that the effect of the moduli on the increase in velocities is not dominantly related to the filling ratio.

In contrast, as seen in Fig. 13, the attenuation shifts from 1.4 to 1.3 (4%) in the case of 0.01 GPa, while the attenuation drastically decreases from 0.8 to 0.4 (50%) in the case of 10 GPa. Thus, it is confirmed that the effect of filling ratio is considerably high on the attenuation, in the case that the stiffness of the healing layer is high.
It is clarified that the velocity of longitudinal wave and the attenuation of waveform are differently associated with the stiffness and filling ratio of the healing layer. These results suggest that the conditions of the healing layer could be estimated from these wave parameters, based on the results of simulation analysis. For example, because the velocity is not dominantly associated with the filling ratio of healing layer, the stiffness is to be reasonably estimated from the measured velocity. Further, from the relation between the filling ratio in each stiffness and the attenuation, the filling ratio is to be estimated. In the present research, the velocities measured in the experiments are not in close agreement with results of the simulation analysis. This is because inherent errors of arrival times could exist due to setting the threshold to eliminate the noises in the experiment. It should also be added that concerning the model of healing layer in the crack is limited to the shape of the transverse band. With respect to actual cases, other models are to be taken into consideration. In addition, the effect of frequency range is to be discussed and established. Besides, except for the velocity, the attenuation is closely related with the effect of Rayleigh waves. Since this is dispersive, a relation of the wavelength is to be clarified in future.

5 Conclusion

By employing mortar specimens with cracks, the effect of self-healing is investigated through ultrasonic measurements. As for healing materials, superabsorbent polymers (SAPs) and nanosilica (HS40) were applied. After wet-dry curing of these materials, recoveries of the longitudinal wave velocity and the attenuation were confirmed. These results are analytically verified. Achievements are summarized, as follows:

1. In the simulation analysis, with the increase in the moduli of healing layer, it was confirmed that the velocity increases and the attenuation decreases.
2. Concerning the values of the velocities in the model were higher than those of the experiments, as observed in a previous study with 2D models. This might be associated with the effect of threshold level to eliminate the environmental noise.
3. From the comparison of attenuations between experiments and simulations, it was estimated that the stiffness of healing layer at 28-day curing was 0.01 GPa with SAP and 0.5 GPa with SAP and HS40. In addition, the effect of reflections was minor in the velocity, while it was important in the attenuation.
4. The effect of filling ratio on the velocity was found to be smaller than 10 %, as for variations between 5 % and 100 %.
5. Concerning the attenuation, the effect of filling ratio was small in the case of low stiffness (0.01 GPa). The effect becomes larger in the case of high stiffness (10 GPa), i.e. a 50 % decrease due to the variations from 5 % to 100 %.
6. The longitudinal wave velocity and the attenuation of waveforms were differently associated with the stiffness and filling ratio of healing layer. These could lead to the conclusion that the conditions of the healing layer could be estimated from these wave properties, based on the results of simulation analysis.

References