Influence of ultrasonic frequency on the evaluation of self-healing and repair in concrete

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Abstract. Self-healing and repair of cementitious media entails restoration of mechanical properties. However, testing of the effectiveness of the process is not straightforward. Microscopy, and computed tomography can potentially verify the deposition of healing/repairing material in the crack, while other tests like water permeability evaluate the "sealing" properties. However, they do not supply information on the mechanical performance of the healed or repaired layer. It is only possible to check mechanical properties by re-loading, but this cannot be used in-situ while the monitoring of continuous healing cannot take place on the same specimen even in laboratory since the measurement is destructive. This is the research gap that ultrasound can fill. Since elastic waves physically propagate through the material, they gather information on the elastic properties of the different constituents. Ultrasound has been recently used to monitor the healing and repair effectiveness in cementitious materials and structures. The present paper addresses the importance of the applied frequency in different modalities. In one-sided measurements, the wavelength defines the Rayleigh wave penetration and therefore a modification of the frequency defines the depth of material that can be characterized. On the other hand, in through transmission, the wavelength defines essentially the resolution of the technique. This becomes very important for heterogeneous materials and specifically, for crack interfaces at various conditions, like totally empty -acting as discontinuities-, having bridging points between the sides, and partially or fully healed.

1 Introduction

Repair is essential to structures and when properly conducted, it can substantially increase the service life, saving resources in raw materials for new construction, capital, working hours, while it also eliminates the problem of recycling of the material of the old structure for a given period [1]. It can take place with dedicated actions, like bonded overlays [1], injection of repair agent [2-3], as well as self-healing that occurs naturally, or is stimulated by some additives in the matrix, like superabsorbent polymers and nanosilica [4]. However, the effectiveness of repair should be examined in order to validate the restoration of material properties or that it has fulfilled the initial purpose. Due to the heterogeneity of the structures and the geometrical conditions, this is not always a straightforward task. In most of the cases, visual inspection would not suffice the requirements, as for example in cases where repair agent is injected into the cracks, or the cracks close due to self-healing. Quantification of the repair effectiveness is important for further operation of the structure.

In case of manual repair by injection, the voids are filled, increasing the loadbearing cross-section while the cracks are sealed. The volume of the injected material can be controlled or measured; however, the volume of the crack or the crack network that was eventually filled cannot be a priori known. In the case of self-healing the precipitation of healing products inside the crack is also not controllable. Therefore, an assessment must be done at the surface and requires information from the interior of the structure. In this case, elastic waves have proven very useful. Apart from their non-invasive nature, their advantage is that they physically propagate through the material and therefore, collect information on the elastic modulus and density of the constituents. In a three-dimensional wave propagation case, the velocity C of longitudinal waves is connected to the elastic modulus E, the density ρ, and the Poisson's ratio ν through the following fundamental relation [5]:

$$C = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{1}$$

Waves can physically propagate though solid media like concrete with velocities of the order of 4000 m/s in intact state. However, when damage is included in the path, the propagation is much slower, while anyway transmission is reduced due to attenuation. Therefore, variations in the wave velocity can be used to demonstrate the stiffness of the propagation path and its general condition [6-7]. Since concrete is heterogeneous, the wave propagation is dispersive, meaning that the pulse velocity depends on the

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frequency, while the amount of damage contributes to this dispersive behaviour. Dispersion has been studied as it shows the potential to increase the characterization capacity in intact and damaged concrete [6,8]. In the following, some examples of ultrasonic investigation of repair or self-healing using more delicate frequency information are discussed.

2 Assessment of repair through epoxy injection

In case of specific defects like through the thickness cracks in a concrete slab or bridge deck, wave application could successfully evaluate the difference between the damaged situation of the member and the repaired state after epoxy injection. In [9], groups of five sensors were arranged at the top and at the bottom surface (Fig. 1) of a bridge deck. Excitations were made at each sensor position and the propagating wave was recorded at all other sensors positions.

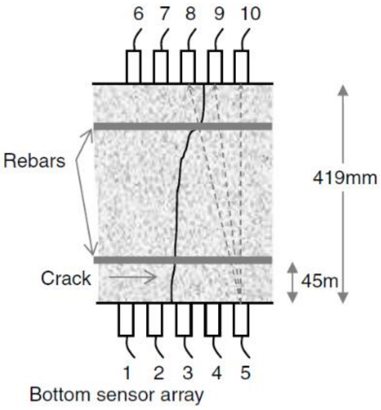


Fig 1. Side view of the sensor location and crack position through the bridge deck [9].

Reasonably, wave paths that are not intersected by the crack exhibit higher velocity than the ones including a crack. Combining the information of transit time of all the different wave paths in the tomography procedure, the visualization of the velocity structure of the cross-section is conducted (see Fig. 2 (a)). In the initial tomogram, the crack is clearly visible, being associated with much lower wave velocity (measured by simple threshold crossing) than the sound material away from the crack. After repair, the overall velocity map has substantially increased since the void was filled and there are only traces of the crack still visible (Fig. 2 (b)), something normal because the epoxy, even though exhibiting higher strength than concrete, has a much lower elastic modulus (3 to 5 GPa). Nevertheless, the information supplied by the ultrasonic tomogram is sufficient to realize that the filling was satisfactory and allowed the continuation of the works.

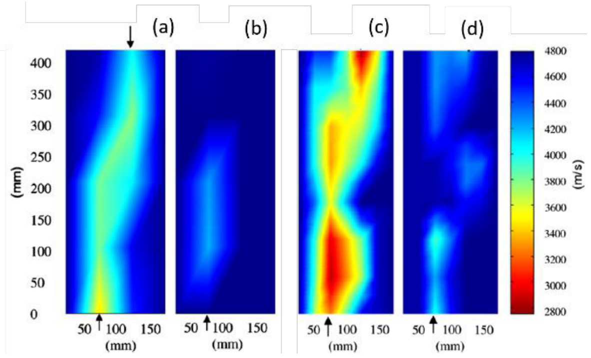
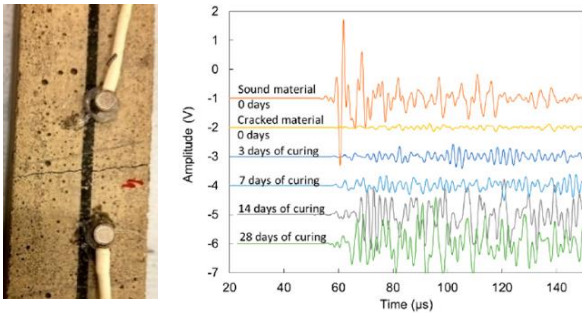


Fig. 2. Ultrasonic tomograms based on first threshold crossing velocity (a) before repair, (b) after repair with epoxy injection in the crack. Ultrasonic tomograms (c) before and (d) after repair based on the wave velocity of 100 kHz [9].

In an advancement of the method, the phenomenon of dispersion was exploited. This takes advantage of the fact that the wave velocity is not constant with frequency in heterogeneous media. Therefore, some frequencies can be more indicative of damage or restoration. In case a relatively broadband pulse is applied, dispersion analysis enables pinpointing which is the frequency band that increases the characterization potential or practically that exhibits larger difference between cracked and sound material. In the specific case, tomograms based on wave velocities at 100 kHz, showed the crack in good geometric accuracy, the range of velocity values was much increased (2800 m/s for cracked and 4800 m/s for sound) making the differences sharper (Fig. 2 (c)), while the remaining traces from the repair were more evident (Fig. 2 (d)).

3 Self-healing evaluation using ultrasound

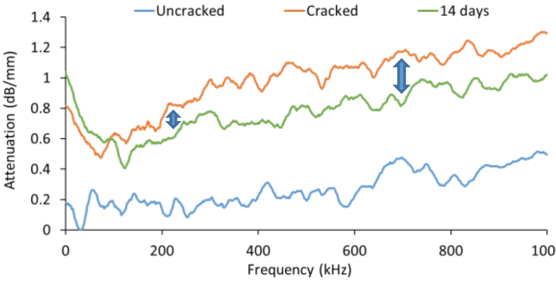
Using ultrasound, it is also possible to monitor restoration of mechanical properties due to self-healing instead of manual repair. Healing can take place in cementitious materials inherently due to delayed hydration and precipitation of $CaCO_3$ in the cracks. Nevertheless, this can be enhanced by additives like superabsorbent polymers (SAPs) or nanosilica, like in the specific case of [10]. In order to create the initial crack, the mortar specimens were fractured by tensile loading after curing of 28 days. Later they were placed in wet-dry cycles to promote healing and ultrasonic properties were monitored from the surface, mainly wave velocity and amplitude. Two relatively broadband sensors with peak frequency of 450 kHz were attached on the surface at both sides of the crack (see Fig. 3 (a)) and the excitation was conducted by pencil lead breaks. It was clear that a sharp decrease in velocity and amplitude was noticed after cracking (Fig. 3 (b) - waveform "Cracked material 0 days"), while later with the progress of healing, the wave amplitude and velocity were partially restored.



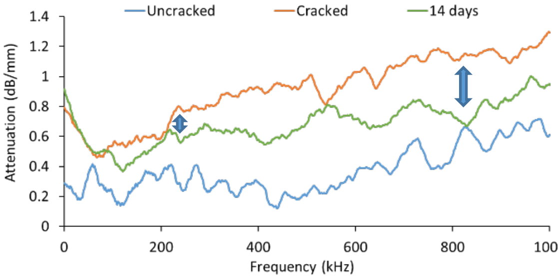
(a) (b)

Fig. 3. (a) "Pico" sensors placed at both sides of the crack in a mortar specimen and (b) waveforms received for different conditions of the cracking and healing ages [10].

Since self-healing strongly depends on the conditions and specifically the availability of water, it is normal that it is more effective on the surface of the specimens rather than deeper inside the crack. This can be checked using the above-mentioned surface wave set-up. The reason is that surface or Rayleigh waves penetrate at a depth roughly equal to their wavelength and therefore, pulses of short wavelengths (or high frequencies) are more indicative of shallow layers, while long wavelengths or low frequencies collect information from deeper layers as well. Fig. 4 (a) shows the attenuation curve for reference mortar specimens before cracking, after cracking and 14 days after wet-dry healing cycles [4]. The initial curve is at relatively low values and shows an increasing trend as normally the higher frequencies are more effectively damped and scattered. As expected, the through-the-thickness crack sharply increases the level of the apparent attenuation by about 5 times (i.e. from approximately 0.2 dB/mm to 1 dB/mm). The wet-dry cycles until 14 days have a certain decreasing effect on the attenuation. Since healing products are precipitated in the crack, wave transmission is partially restored and the attenuation curve is translated downwards. Furthermore, it is indicative that higher frequencies show a stronger decrease after healing, than lower ones. Indicatively, attenuation drops by approximately 0.2 to 0.3 dB/mm at the zones around 800 kHz, while it drops by about 0.1 dB/mm around 200 kHz. Fig. 4 (b) shows the corresponding attenuation curves for mortar including nanosilica particles [4]. These particles can act as nucleation points that stimulate further hydration and have been used to increase healing. In this case, the drop of attenuation at high frequencies is even higher, i.e. more than 0.4 dB/mm, while at low frequencies the difference is between 0.1 to 0.2 dB/mm. This confirms that the deposition of healing products is more effective in a layer of 3 mm depth (Rayleigh wavelength of 800 kHz), while wavelengths propagating as deep as 10 to 11 mm (200 kHz) show less restoration.



(a) Reference



(b) Nanosilica

Fig 4. Attenuation vs. frequency curves for uncracked, cracked and 14 days of wet-dry healing of (a) reference mortar and (b) mortar with nanosilica [4].

Another testing series focused on the evaluation of self-healing by monitoring mortar cubes through ultrasonic transmission measurements at different frequencies. Mortar cubes with 100 mm side including SAPs were investigated. On opposing planes, a grid of 7 by 7 points was drawn, which indicated the measuring locations (see Fig. 5.). The set-up consisted of two sensors, one emitter and one receiver, which were moved step by step from one point to the other to create a map of the longitudinal wave velocity over the entire surface. Additional details can be found in [11]. Two types of sensors were adopted, namely two R15α sensors with peak frequency of 150 kHz and two broadband sensors with central frequency around 450 kHz. The emitted wave signal was created through a waveform generated and was equal to a single cycle sine wave with frequency 150 kHz and 400 kHz, depending on the sensor type used.

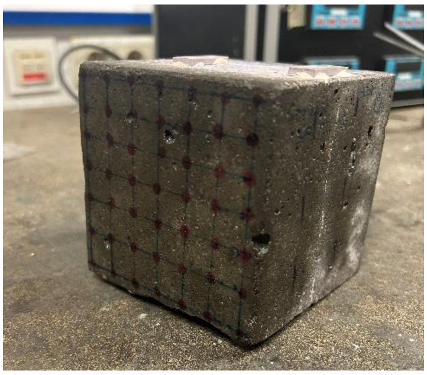
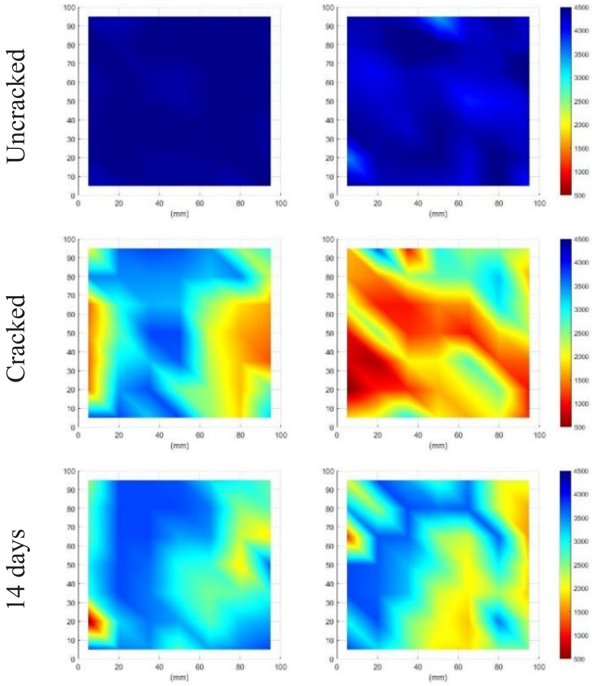


Fig. 5. Cubic mortar specimen used for self-healing assessment through ultrasonic transmission measurements.

Ultrasonic measurements were conducted in the intact state, after cracking and after 14 days in wet-dry curing cycles. The fracturing of the specimens was achieved through a Brazilian splitting test, leading to two halves that were re-assembled afterwards by using metal tabs and glue. The gluing was performed by placing the specimens underneath an optical microscope, to receive an average crack width between 150 µm and 250 µm.

For every conducted measurement, the longitudinal wave velocity was calculated and colour maps were plotted to visualize the variability of the velocity over the entire cross section. The various states, assessed through a frequency of 150 kHz and 400 kHz, are depicted in Fig. 6 (a) and (b), respectively. In the uncracked situation, both colour maps show a relatively homogeneous distribution of the wave velocity. For 150 kHz, the velocity was approximately equal to 4500 m/s in all regions, and the evaluation through the higher frequency of 400 kHz revealed zones with lower wave velocities, i.e. between 3500 m/s and 4000 m/s.



(a) 150 kHz (b) 400 kHz

Fig. 6. Longitudinal wave velocity obtained after ultrasonic transmission measurements in the uncracked, cracked and healed state for (a) 150 kHz and (b) 400 kHz. The velocity values in the colorbar are given in m/s.

After cracking, it can be noticed from Fig. 6 that the velocity lowered drastically for any frequency utilized, which is caused by the created discontinuity. However, it is seen that much lower wave velocities were obtained for the frequency of 400 kHz. This phenomenon can be explained by the increased sensitivity of ultrasonic waves with higher frequency (smaller wavelength) to the defect. In addition, the amplitude of these sensors is lower due to their more broadband nature, implying that the first threshold crossing might not indicate the first cycle of the received signal. Therefore, this is an indirect effect that results in the large velocity decrease. Later on, after 14 days of wet-dry healing cycles, the velocity was partially restored in most regions, which could be observed from both testing methodologies. Again, the values of the longitudinal wave velocity remained smaller in case of 400 kHz compared to 150 kHz. While the internal pattern of the crack could not be confirmed, in both cases lower velocities are seen at the right part of the cross section, implying a bigger crack volume. The average velocity for the three stages (intact, cracked, partially healed) is shown in Fig. 7. It is seen that both frequencies provide a clear trend for cracking and healing, while the 400 kHz shows higher sensitivity to the material condition, as their corresponding velocity decreases more with damage and increases more with healing. Specifically, for 150 kHz, the healing recovery after cracking is of the order of 300-400 m/s, while for the 400 kHz, it is 800 to 900 m/s offering more characterization power.

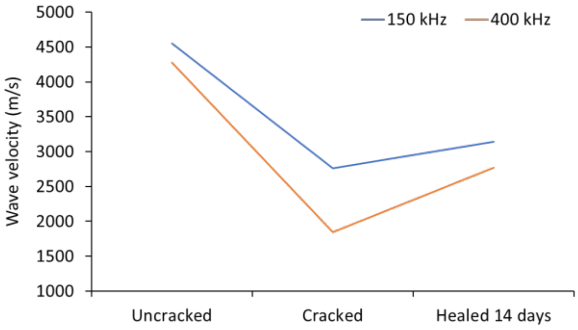


Fig. 7. Ultrasonic velocity at different frequencies and three stages of the material

These results confirm the potential of ultrasound to assess the self-healing ability of cementitious mixtures and are indicative for the sensitivity of various frequencies to the present condition of damage or repair, either in through-transmission or surface mode.

4 Conclusions

Ultrasound is an adequate way to monitor processes that involve stiffness change, like cracking and healing or repair in general. Wave velocity is a relatively simple parameter that can be measured in the laboratory or by commercial probes in the field. While its effectiveness is proven, strong improvements can be derived by manipulation of the frequency. This can be conducted by using different transducer or changing the electric excitation signal. In the present paper, the change of the frequency of longitudinal waves allowed to more accurately characterize the cracking shape and restoration after manual epoxy impregnation on a bridge deck, while it showed better characterization capacity for self-healing cementitious media in the laboratory. In addition, different frequencies applied in surface waves, exhibited better restoration of properties near the surface of the specimens than in deeper layers. Ultrasound offers a non-invasive and simple manner to evaluate the healing and repair of cement-based media in laboratory, while enables applications in-situ.

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References

1. S. N. Bousias, *Repair/retrofitting of concrete structures with fiber-reinforced polymers*, in Failure, distress and repair of concrete structures (Woodhead Publishing, 2009)
2. M. Raupach, *Standards and guidelines for repairing concrete structures*, in Failure, distress and repair of concrete structures (Woodhead Publishing, 2009)
3. C. A. Issa, *Methods of crack repair in concrete structures*, in Failure, distress and repair of concrete structures (Woodhead Publishing, 2009)
4. G. Lefever, Superabsorbent polymers and nanosilica for mitigation of autogenous shrinkage and promotion of self-healing of cementitious materials PhD Thesis, Vrije Universiteit Brussel (2020)
5. T. R. Naik, V. M. Malhotra, J. S. Popovics, *The ultrasonic pulse velocity method*, in Handbook on Nondestructive Testing of Concrete (2003)
6. J.-F. Chaix, M. Rossat, V. Garnier, G. Corneloup, Journ Acoust Soc America, **131**, 4481-4490 (2006)
7. E. Ahn, H. Kim, S. H. Sim, S. W. Shin, M. Shin, Mater, **10**, 278 (2017)
8. T. P. Philippidis, D. G. Aggelis, Ultrason, **43**, 584-595 (2005)
9. D. G. Aggelis, T. Shiotani, Cem Concr Compos, **29**, 700-711 (2007)
10. G. Lefever, D. Snoeck, N. De Belie, S. Van Vlierberghe, D. Van Hemelrijck, D. G. Aggelis, Sensors, **20**, 2959 (2020)
11. G. Lefever, D. Van Hemelrijck, D.G. Aggelis, D. Snoeck, Constr Build Mater, **344**, 128272 (2022)