Airborne ultrasounds for damaged cementitious characterization

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Abstract

The scope of this paper is to demonstrate the capability of airborne non-contact ultrasound (ANC-US) to assess thermal damage on normalized Portland cement mortar specimens. For this purpose, contact ultrasound (C-US) and ANC-US are compared. A normalized dosage mortar was carried out to obtain standardized mortar specimens of 4 x 4 x 16 cm. Then, they were measured by ANC-US and C-US. Afterwards, they were thermal damaged (400º C) and measured again. Ultrasound velocity and frequency attenuation were estimated. As expected, damaged samples show lower velocities and higher attenuations than sound samples. It is remarkable how the attenuation keeps constant for frequencies below 100 kHz and increases due to the sensitivity of higher frequencies to the size of thermal microcracking.

Although ANC-US does not require any coupling media as C-US does, it requires additional calibration to compensate propagation through the air and material boundaries. Considering these terms, both techniques offer consistent results and the capability of ANC-US technique for damage characterization in cementitious systems is proved.

Keywords
Airborne ultrasounds, material characterization, mortar, signal processing, thermal damage

I. Introduction

Due to its good performance against high temperatures, concrete is one of the most used materials in fire-resistant structures in civil and building engineering [1]. Despite the goodness of this material, the cement paste that binds the sand particles and coarse aggregates losses stiffness and adhesion capacity when the temperature is significantly high. Because of the multiple causes that can affect the integrity of concrete under thermal damage, the development of Non-Destructive Testing (NDT) techniques may help to evaluate the internal state of concrete and becomes a hot-spot [2][3].

NDT techniques can be classified according to the method for measuring the target scope of the structure. Beginning from mechanical waves, there are techniques for the purpose of overall inspection (ultrasonic, impact echo) and techniques for the purpose of surface evaluation (Schmidt rebound hammer, spectral analysis of surface acoustic waves [4]. Other techniques focus on the response of specific points by obtaining concrete samples. Focusing on ultrasound testing, pulse velocity and attenuation measurements can be performed in the field with relative simplicity and give interesting and specific information about the stiffness of the material and the scattering components. Due to its robustness, ultrasonic pulse velocity is widely used [3][5]. However, attenuation is considered more sensitive to the structural properties of the material although it is more easily affected by variability in the experimental setup than ultrasonic velocity, such as coupling problems, energy loss due to cables and variability between sensors. Such variables become essential to evaluate thermal damage on concrete, giving information about multiple processes inside the concrete elements [6][7][8]. A common setup is through-transmission contact ultrasound (C-US), where the inspected material is clamped between the transmitter and the receiver transducers and requires a coupling medium (usually water-gel, petroleum jelly or similar). The more recent airborne non-contact ultrasound (ANC-US) [9] technique is similar to C-US but the transducers are separated respect to the inspected material by an air gap. Therefore, it does not require any liquid coupling, but additional effects occur that have to be compensated [10].

The scope of this paper is to demonstrate the capability of ANC-US to assess thermal damage on normalized Portland cement mortar specimens. For this purpose, C-US and ANC-US are compared.

II. Methodology

II.1 Mathematical background

The estimated ultrasound parameters are the wave velocity and the attenuation of the material. The propagation velocity, v_p, is obtained as the ratio between the length of the specimen, d_{mat}, and the signal time arrival, t_a, Eq. (1).

$$v_p[m/s] = \frac{d_{mat}\ [m]}{t_a\ [s]} \tag{1}$$

Frequency dependent attenuation curve profile is estimated considering the difference between the transmitted ($S_{tx}(f)$ [dB]), received pulse ($S_{rx}(f)$ [dB]) and the system response ($\alpha_{cal}(f)$), divided by the thickness of the specimen (d_{mat}), Eq. (2) [10].

$$\alpha_{mat}(f)[dB/cm] = \frac{S_{tx}(f)[dB] - S_{rx}(f)[dB] - \alpha_{cal}(f)[dB]}{d_{mat}[cm]} \tag{2}$$

The transmitted signal, $S_{tx}(f)$, conditions the frequencies that are injected into the material and, therefore, the frequencies at which $\alpha_{mat}(f)$ can be evaluated. Depending on the setup, the $\alpha_{cal}(f)$ must be estimated in order to consider the effects of involved equipment as well as each particular setup: contact or non-contact. In the case of contact setup, the $\alpha_{cal}^{(C)}(f)$ may be approximated by Eq. (3), where $\alpha_{equip}^{(C)}(f)$ includes the effects of the measurement equipment (cables, amplifier, contact transducer response…) meanwhile $\alpha_{B}^{(C)}(f)$ includes the attenuation due to the transducer-specimen boundaries.

$$\alpha_{cal}^{(C)}(f)[dB] = \alpha_{equip}^{(C)}(f) + \alpha_{B}^{(C)}(f) \tag{3}$$

In the case of non-contact measurement, the expression becomes more complex since additional attenuation terms must be added, Eq. (4), $\alpha_{air}(f)(d_1 + d_2)$ [dB] represents the ultrasonic absorption in air, $\alpha_{B_{in}}(f)$ [dB] and $\alpha_{B_{out}}(f)$ [dB] represent the attenuation of the air-material boundaries, and $\alpha_{S_{in}}(f, d_1)$ [dB] and $\alpha_{S_{out}}(f, d_2)$ [dB] represent the energy loss due to beam spread.

$$\begin{aligned}\alpha_{cal}^{(NC)}(f)\ [dB] = {} & \alpha_{air}(f)(d_1 + d_2) + \alpha_{S_{in}}(f, d_1) + \alpha_{B_{in}}(f) + \alpha_{B_{out}}(f) + \alpha_{S_{out}}(f, d_2) \\ & + \alpha_{equip}^{(NC)}(f)\end{aligned} \tag{4}$$

II.2 Experimental

A normalized dosage mortar was carried out to obtain 2 specimens. The standardized mortar pieces (4 x 4 x 16 cm) were stored in a wet chamber for 60 days in order to reach stabilization stage. Then, they were dried to constant mass and were measured by ANC-US and C-US. Afterwards, the specimens were heated in an oven for 3 hours up to 400º C. The thermal damaged pieces were measured again with both techniques.

II.3 Contact ultrasound layout

The layout for the contact measurements is shown in Figure 1. The transducers were broadband K1SC from General Electric centered at 1 MHz. The transmitter stage was an arbitrary signal generator (Handyscope HS3) attached directly to the transmitting transducer. The receiving transducer was connected to a linear amplifier with a gain factor of 32dB

(Panametrics) and a single broadband signal (20kHz to 1MHz) was used. The received signal was captured by a digital oscilloscope (Handyscope HS3) with a sampling frequency of 50 MHz and 20,000 samples. Finally, a laptop was used to control and to store the signals. Petroleum jelly was used as an impedance coupling medium.

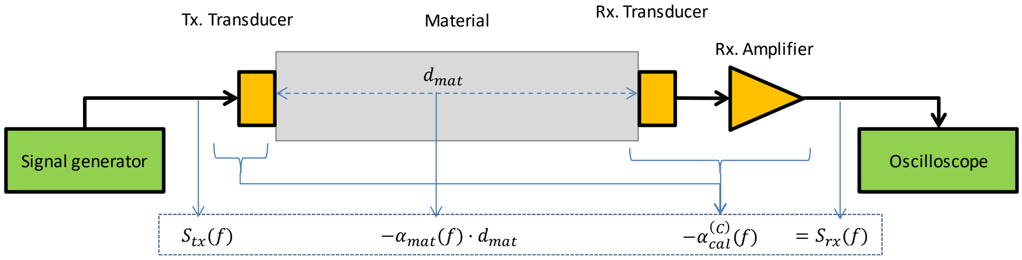

Figure 1. Contact setup

II.4 Non-contact ultrasound layout

The layout of the air-coupled measurements is shown in Figure 2. The used transducers were designed and lent by the Institute for Physical and Information Technologies ITEFI-CSIC. Both of them were piezoelectric transducers with matched layer for air transmission centered at 250 kHz. The transmitter transducer was excited by a programmable signal generator (Handyscope HS3) plus a linear amplifier of 50 (Falco system WMA-300). A broadband signal (100 kHz to 500 kHz) was used. The receiver transducer was connected to a linear amplifier of 40 dB (Panametrics). The received signal was captured by a digital oscilloscope (Handyscope HS3), with a sampling frequency of 10 MHz and 20,000 samples. A laptop was used to control and to store the signals. The transmitter and receiver transducers were separated by 16 cm (d_1, d_2) each from the specimen and the perimeter of the specimen was covered by sound absorbing foam.

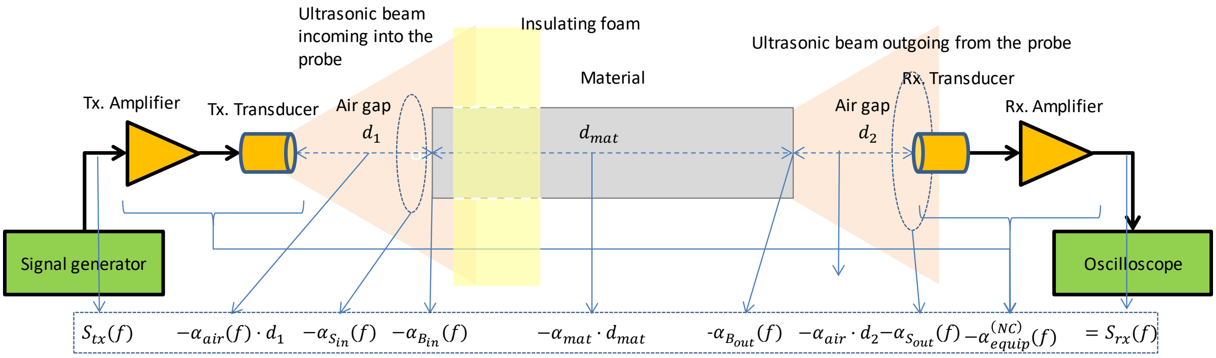

Figure 2. Non-contact setup

For both layouts, the calibration process described in [10] was carried out to obtain $\alpha_{cal}^{(C)}(f)$ and $\alpha_{cal}^{(NC)}(f)$. Each sample has measured along its main axis 15 times but from the two directions, that means 30 measurements for each sample, state and technique.

III. Results

The longitudinal wave velocities for the samples are obtained from contact measurements and are shown in Figure 3. As expected, the thermal damage generated microcracks that reduces the global velocity of the damaged samples up to 50% (2000 m/s) respect to the sound samples (4000 m/s). On the other hand, the results of attenuation profile are shown in Figure 4. Firstly, it can be noted that both techniques offer similar curves and trends for sound and damaged samples. Secondly, the NC-technique does not offer reliable results below 100 kHz due to its poor signal to noise ratio. But over this frequency, both techniques offer similar results and trends and the samples present a linear increment from 100 kHz to 200 kHz, but the damage samples present greater attenuation. Below 100 kHz there is only results for the contact technique, but the reader can notice that there is no difference between sound and damage samples as an indication of the size of the thermal microcracking.

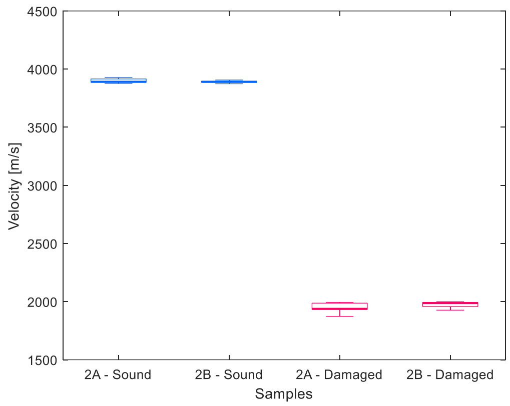

Figure 3. Boxplot of velocities for C-US

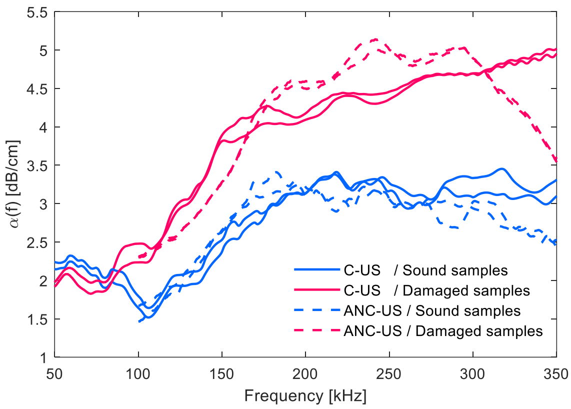

Figure 4. Attenuation for C-US and ANC-US

IV. Conclusions

This work demonstrates the capability of the ANC-US technique for the evaluation of cement samples respect to the traditional contact technique. Although the non-contact technique requires a more sophisticated processing and it suffers a greater attenuation, it avoids the physical contact with the tested sample. This fact supposes a huge advantage for automatization processes. Additionally, the capability of the ultrasound for the evaluation of thermal damage has also been proved. The velocity is reduced by 50% and the attenuation is sensitive to this type of damage for frequencies over 80 kHz.

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