Ultrasonic characterization of small-sized concrete laboratory specimens

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Abstract

Characterization of small-sized concrete laboratory specimens is discussed. It could be performed through analysis of its scattering properties (diffusivity) that allow to qualify its state of health. In such situation, it is impossible to separate multiple-scattering and reverberation contributions in ultrasonic signals. The methods based on the fit of the diffusion equation are not always relevant, leading to a wrong interpretation of the diffusion constant. A new method is thus proposed, taking advantage of a geometrical phenomenon: the Coherent Reverberation Enhancements. Indeed, those enhancements are expected to evolve with the scattering states of the material. 2D numerical simulations of concrete specimens with various aggregates densities were carried out. The first results validate the method: the CRE values are sensitive to the scattering properties of the material. This is therefore a simple and elegant way to characterize a scattering reverberant medium.

1. Introduction

A good management of civil engineering and building infrastructures depends on a reliable diagnosis about their state of health. Many of them are made of concrete. Ultrasonic waves have shown over the recent years a promising potential for NDT of concrete material. Due to the complex random heterogeneous structure of concrete, ultrasonic waves are scattered by all heterogeneities (aggregates) contained in the mortar, in all directions, allowing to probe a large volume. In such a scattering medium, the ultrasonic wave loses phase's information and the memory of its initial direction of propagation after many paths of propagation. The ultrasonic mean intensity then evolves as the diffusion halo of heat [1, 4, 5]. Many authors [1, 2, 3] analyze the evolution of the ultrasonic intensity using the diffusion equation to extract parameters as diffusivity and dissipation in order to characterize the concrete. The diffusivity indeed measures the scattering power of the material, so is linked to its microstructure, and consequently to its state of health [3]. The dissipation, for its part, mainly quantifies the viscoelastic properties of the cement paste which may be affected by some damages or pathologies [3]. However, those methods imply that measured ultrasonic signals only contain multiple-scattering contributions from the scatterers (aggregates). That is the case for sufficiently large medium. The case of small-sized laboratory specimens is more complex. The ultrasonic intensity indeed contains both contributions from the concrete structure (multiple-scattering) and from the specimen geometry (reverberation from boundaries). The reverberations even dominates the signals. An important question arises: does the diffusivity usually measured with the temporal fit of the diffusion equation characterize, this time, the microstructure of the scattering reverberant medium, or is it governed by its geometry? Those methods have meaning only if the diffusive regime has been reached. Unfortunately, unless the medium is extremely scattering, it takes place at the later part of the signals. And a rise of the mean intensity at early time will be only attributed to a geometry effect rather than the diffusion halo's growth. There are therefore many constraints with those methods.

Theoretical studies and numerical simulations were carried out to propose an alternative approach to characterize small-sized concrete laboratory specimens. This new method takes advantage of reverberations instead of removing them. Analog to the Coherent Backscattering Enhancement (CBE) in random media [4, 5], constructive interferences between specific reverberation paths lead to an enhancement of the averaged intensity at the emission point [6]. For specimens with regular geometries, other enhancements are localized at symmetric points [7]. Due to the presence of scatterers, some specific reverberation paths vanish. Hence, the so-called "Coherent Reverberation Enhancements (CRE)" are expected to decrease as density of scatterers increases. The paper is organized as follows. Firstly, the differences between multiple-scattering and reverberation are explained. Secondly, the two coherent phenomena (CBE and CRE) and their potentials for material's characterization are explained. And finally, the potential of the CRE for characterizing scattering reverberant media is established with numerical simulations and application of this approach to small-sized concrete specimen is discussed.

2. Diffuse ultrasound : multiple-scattering vs reverberation

In concrete, due to impedance differences between mortar and aggregates, ultrasonic waves are multiply scattered by the aggregates. This frequency dependent phenomenon is very dominant in the "stochastic" scattering regime that is when the ultrasonic wavelength is close to the scatterers sizes. This is the case for ultrasonic concrete inspections carried out at the frequency range [250-750 kHz]. The multiple-scattering process is energy conservative: the energy is gradually transferred from the "coherent part" of the wave which contains phase information, to the "incoherent part" usually called coda. After sufficient time of propagation, the coherent part vanishes (elastic mean free time) and there is no more preferred direction (transport mean free time). The ensemble averaged intensity I is then assumed to evolve according to a solution of the diffusion equation [3]:

$$\frac{\partial I}{\partial t} - D\Delta I + \sigma I = P \qquad (1)$$

Where D [$m^2.s^{-1}$] is the diffusivity - closely linked to the material's microstructure – and σ [s^{-1}] is the dissipation - linked to the viscoelastic properties of the material. P is the source term.
The solutions of the Equation (1) for a finite medium, i.e. with Dirichlet boundary conditions, are obtained in 2D by modal decomposition [2]:

$$I(x,y,t) = \left\{ \begin{array}{c} 1 + \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} 4\cos\left(\frac{n\pi x_0}{a}\right)\cos\left(\frac{m\pi y_0}{b}\right)\cos\left(\frac{n\pi x}{a}\right)\cos\left(\frac{m\pi y}{b}\right) \\ \times e^{-D\left[\left(\frac{n\pi}{a}\right)^2+\left(\frac{m\pi}{b}\right)^2\right]t} + \sum_{n=1}^{\infty} 2\cos\left(\frac{n\pi x_0}{a}\right)\cos\left(\frac{n\pi x}{a}\right) e^{-D\left[\left(\frac{n\pi}{a}\right)^2\right]t} \\ + \sum_{m=1}^{\infty} 2\cos\left(\frac{m\pi y_0}{b}\right)\cos\left(\frac{m\pi y}{b}\right) e^{-D\left[\left(\frac{m\pi}{b}\right)^2\right]t} \end{array} \right\} I_0 e^{-\sigma t} \quad (2)$$

And in similar way for 3D configuration [8]:

$$I(x,y,z,t) = \left\{ \begin{array}{c} 1 + [g(x,x_0;a)g(y,y_0;b)g(z,z_0;c)] \\ +[g(x,x_0;a) + g(y,y_0;b) + g(z,z_0;c)] \\ +[g(x,x_0;a)g(y,y_0;b) + g(x,x_0;a)g(z,z_0;c) + g(y,y_0;b)g(z,z_0;c)] \end{array} \right\} I_0 e^{-\sigma t} \quad (3.1)$$

with:

$$g(x,x_0;a) = 2\sum_{n=1}^{\infty} \cos\left(\frac{n\pi x}{a}\right)\cos\left(\frac{n\pi x_0}{a}\right) e^{-D\left(\frac{n\pi}{a}\right)^2 t} \quad (3.2)$$

where a, b and c are the dimensions of the specimen respectively along x, y and z-axis, (x_0, y_0, z_0) the coordinates of the source point and t the time variable.
Both multiple-scattering and reverberation phenomena lead to a diffuse field but in different ways. In fact, reverberation comes from multiple reflections on the specimen's boundaries. So, it is a pure geometric regime at the frequency range of interest. It is also necessary to notice that in elastic media, mode conversions from longitudinal waves to transverse waves (or from transverse waves to longitudinal waves) occur at each scattering or reflection event. So, both longitudinal and transverse waves, denoted P-wave and S-wave respectively, coexist and a stabilization of the energy ratio between S-wave and P-wave is an indication of a diffuse field [10].

3. Coherent Backscattering Enhancement (CBE) vs Coherent Reverberation Enhancements (CRE)

In random media such as concrete, the ensemble averaged ultrasonic intensity evolves as the diffusion halo of heat after sufficient time of propagation. However, it is commonly reported in the literature that this mean intensity is enhanced up to twice at the source's position in the spatial distribution of backscattering. This phenomenon, due to coherent interferences that survive after averaging, is called Coherent Backscattering Enhancement (CBE). Some authors [4, 5] propose characterization methods based on a spatial fit of the diffusion halo from backscattering configuration. The halo's width is assumed to grow according to $\sqrt{Dt}$, which offers the possibility to estimate D at each time step. However, for a finite medium, the halo is rapidly saturated and doesn't evolve with time anymore (Figure 1), making the assessment of the diffusivity D impossible.

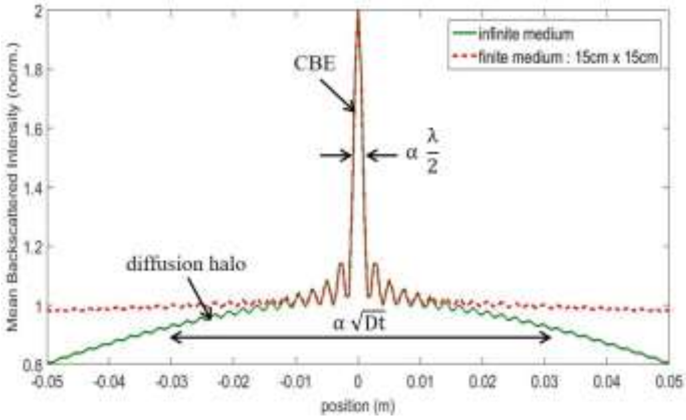


Figure 1. Theoretical spatial profiles of normalized mean backscattered intensities

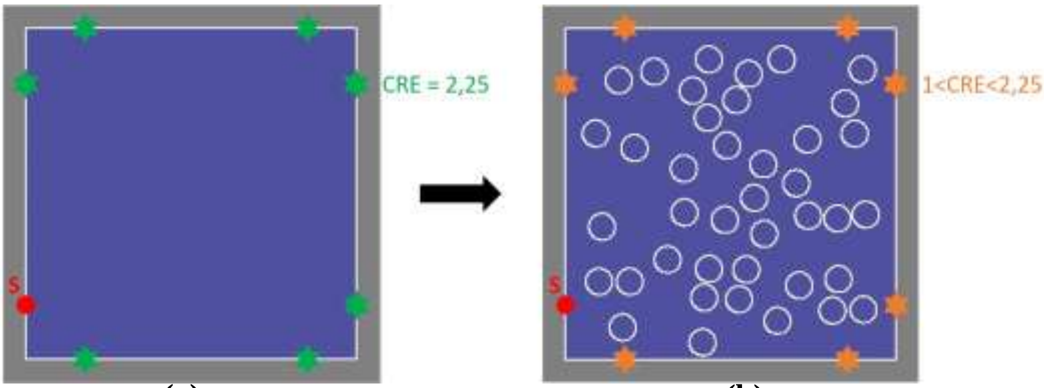
Moreover, in analog to the CBE phenomenon, coherent interferences between specific reverberation paths survive after averaging in a finite medium and lead to an enhancement above twice of the mean intensity at the emission point [6]. In addition to that, another intensity enhancements are symmetrically located depending on the geometry of the specimen. For the simple case of parallelepiped specimens, the theoretical spatial distribution of the averaged intensity can be calculated with the image method or eigen mode decomposition [7]. With the later method, the intensity obtained from time integration, i.e. the energy, is expressed as:

$$I(\vec{r},\overrightarrow{r_0}) = \sum_N \frac{1}{\omega_N^2}\phi_N^2(\vec{r})\phi_N^2(\overrightarrow{r_0}) \quad (4.1)$$

in 2D: $\phi_{mn}(x,y) \approx sin(k_x x)\, sin(k_y y)$, with $k_x = \pi m/L_x \quad k_y = \pi n/L_y$ (4.2)

in 3D: $\phi_{mnp}(x,y,z) \approx sin(k_x x)\, sin(k_y y)\, sin(k_z z)$, with $k_z = \pi p/L_z$ (4.3)

where L_x, L_y and L_z are the specimen's dimensions respectively along x, y and z-axis.
Analytical calculations provide an enhancement factor of 2.25 in 2D and 3.37 in 3D. Those CRE are located at symmetric points of the emission-point (Figure 2a). That is to say, at those specific points, the measured energy will be 3.37 times higher than the energy measured at any other points of a parallelepiped homogeneous medium. The aperture of the CRE is related to the wavelength as it is the case of the CBE [7]. The presence of scatterers inside the medium can destructively interfere with some specific reverberation paths, decreasing the initial CRE values. It is then expected to observe a decay of the CRE as density of scatterers increases (Figure 2b). Numerical simulations are performed to see if this trend is observed in order to further characterize scattering from a scattering reverberant medium such as small-sized concrete specimen.



(a) **(b)**

Figure 2. Decrease of CRE due to the presence of scatterers:
(a) matrix without scatterer: the red-point S is the source and the green stars the initial CRE
(b) matrix with scatterers: the orange stars are the expected decreased CRE

4. Numerical simulations: Characterizing a scattering reverberant media

As a first validation of this new approach, 2D numerical simulations are carried out. To test if various scattering states of the medium can be distinguished. Concrete specimens of size 15cmx15cm are simulated with 12mm diameter aggregates with densities ranging from 0% to 40%. The physical properties of the materials are given in Table 1. The dissipation was not implemented because of the computing time cost. However it won't change conclusions of the study as it is focused on multiple-scattering characterization and the dissipation mainly impacts on the viscoelasticity rather than scattering.

Table 1. Simulated materials properties

	Mortar	Aggregates
C_p (m/s)	3950	4300
C_s (m/s)	2250	2475
ρ (kg/m^3)	2050	2610

All simulations were carried out using software "Prospero" based on 2D finite-difference schemes for wave propagation in complex media. A point-like source emits a Ricker's signal centered at 500 kHz. Figure 3 shows three propagation snapshots at different time steps (0.004ms, 0.04ms and 0.2ms). The "green/red" color code refers to longitudinal waves and the "yellow/magenta" to transverse waves. It can be seen that the transverse waves dominate at later time and no more coherent wavefront is visible. It apparently corresponds to the diffuse field discussed above. Receivers are positioned all around the specimen with 0.5mm spacing in order to get the spatial energy distribution.

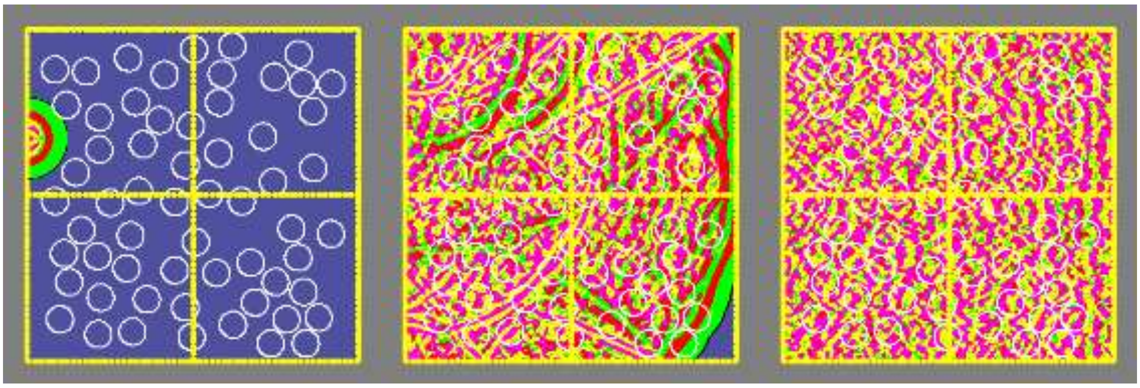


Figure 3. Snapshots at different time steps: 0.004ms, 0.04ms and 0.2ms ; "green/red" color code = P-waves and "yellow/magenta" color code = S-waves ; yellow lines = rows of receivers

Recorded signals (particle velocities) are time integrated, taking necessary precautions to avoid surface waves and first reflections disturbance [7]. Averaging is realized through the time and frequency integrations. The spatial distribution of energy clearly shows the Coherent Reverberation Enhancements as shown in Figure 4:

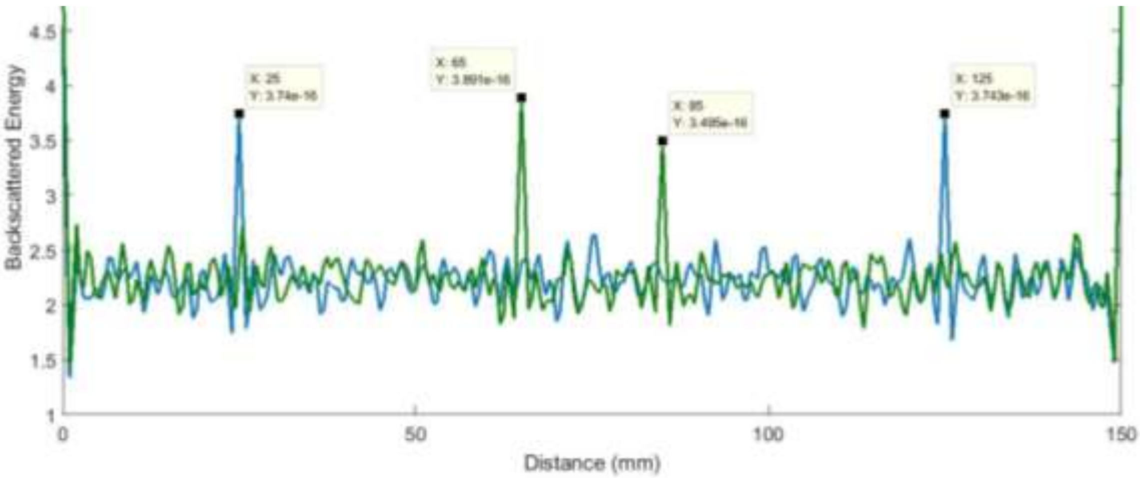
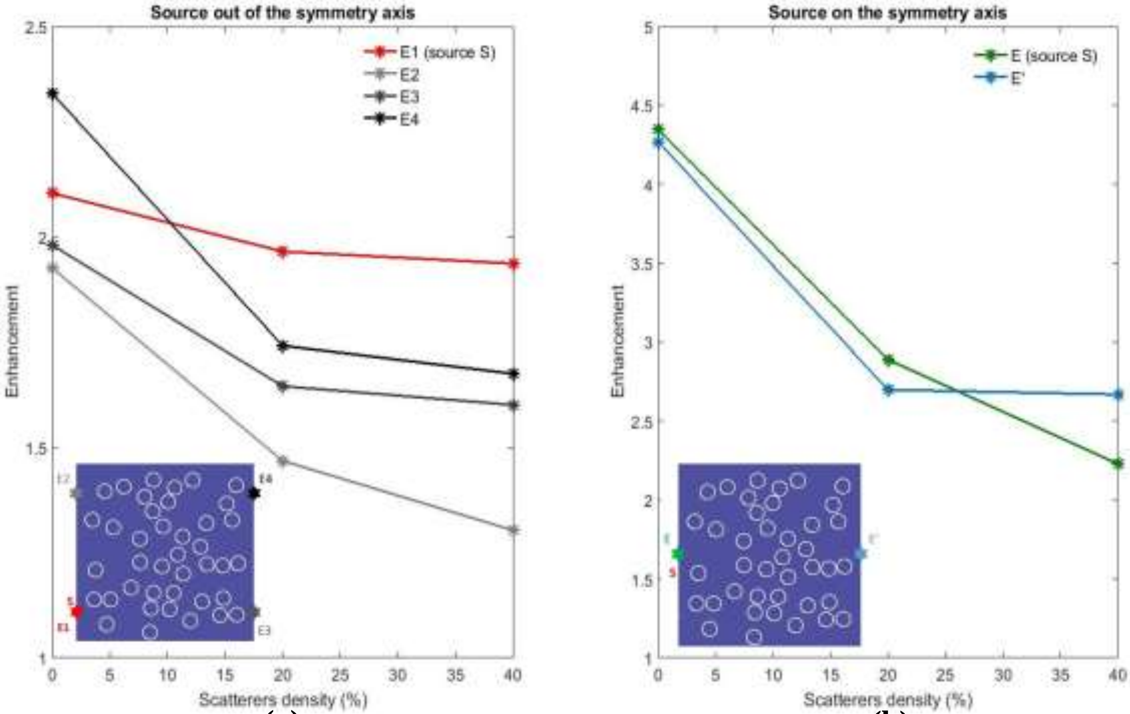


Figure 4. Example of spatial distribution of the backscattered energy ; blue curve: source at 25mm, green curve: source at 65mm

Twenty simulations with different source's positions, for each scatterers density, are then carried out in order to obtain averaged CRE (Figure 5a). Another additional simulation is carried out for an emission point located on the symmetry axis of the specimen (Figure 5b).



(a) **(b)**

Figure 5. Evolution of CRE values according to scatterers density:
(a) for source's positions out of the symmetry axis – (b) for source's position on the symmetry axis

As expected, CRE decreases as scatterers density increases. An exception is noticed at the emission point where it seems to converge to 2 (Figure 5a: E1) the theoretical value of the CBE. Thus, it can be said that the coherent backscattering phenomenon takes over from the coherent reverberation phenomenon as the scatterers density increases. An interesting point is that the information about the medium can be obtained with a backscattering configuration and outside the emission zone (Figure 5a: E2). It will greatly facilitate experimental measurements and furthermore, it seems to be more sensitive to the material's changes compared to the other enhancements. However, it is obvious that the greater the source's positions number is, the more the results are accurate and robust. Another interesting point is that when the source is located at the symmetry axis, the CRE value seems to be doubled (Figure 5b). In this case, the enhancement becomes easier to measure and thus more sensitive.

5. Conclusions

A new method was proposed for the characterization of scattering reverberant media, which is the case of small-sized concrete laboratory specimens. Taking advantage of the coherent reverberation enhancements phenomenon seemed to be a simple and elegant way to characterize the material. First numerical simulations results validated it and experimental measurements are ongoing. Concrete specimens with various micro-cracks densities (linked to increasing thermal damages) are inspected. The surfaces are scanned with a laser in order to map the energy spatial distribution and a point-like transducer is used for emission. This work will not only contribute to the concrete material field but for all material characterizations needs, at any scale, as long as the geometry is regular. It would be used for example in Structural Health Monitoring, where CRE would be sensitive to internal changes.

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