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ULTRASONIC SLOW DYNAMICS TO PROBE CONCRETE AGING AND DAMAGE

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ABSTRACT. The stiffness of concrete experiences a drop immediately after a moderate mechanical solicitation. Then the stiffness rises back logarithmically toward its initial value. This Slow Dynamics behavior has been probed by macroscopic quantities averaged over the sample volume, including resonant frequency. This article presents a different approach based on diffuse acoustic wave spectroscopy, a technique that is directly sensitive to the details of the sample structure. The parameters of the dynamics are found to depend on mechanical and thermal damage of the medium. Results confirm that slow dynamics can be used onsite to assess the level of damage of a given structure.

Keywords: Ultrasonic, Coda Waves, Diffuse Ultrasound, Multiple Scattering, Slow Dynamics, Multicomposite Materials, Aging, Damage.

PACS: 81.05.Rm, 81.70.Bt, 43.50.+y, 43.60.+d

INTRODUCTION

Depending on the level of stress, most solids are well known to have various behavior regimes, including elastic, plastic and eventually brittle regimes. Creep is another possible behavior and occurs when a material is subject to long-term stress (but remains below the yield stress). Creep results in a strain that slowly accumulates. Unlike elasticity, plasticity, brittle and creep deformations are irreversible. In 1996, Johnson and co-authors [1] discovered another regime that consists in a reversible (and repeatable) change after a very moderate strain (at least three order of magnitude smaller than in typical creep experiments). This Slow Dynamics (SD) is logarithmic in time, which means that there is no characteristic time- or length-scale behind this phenomenon. SD has been the subject of continuous interest at the LANL-Solid Earth Geophysics team for at least a decade since then, and has been observed in many multicomposite natural or man-made geomaterials like crystalline rocks, sandstone, limestone or concrete. J. Ten Cate published an elegant review recently [2], where the reader can find many historical and experimental facts on Slow Dynamics.

A typical experiment consists in studying of the resonant frequency of a sample under various levels of solicitation. The solicitation is a sinusoidal drive at acoustic frequencies (around the first resonant mode, for instance). The eigen-frequency is tracked

while the level of solicitation, say the amplitude of the sinusoidal wave, is increased or decreased. In Fig. 1 we draw a schematical view of the experiment, along with the typical temporal evolution of the resonant frequency. The typical duration of the experiment is of the order of several minutes to hours, and the typical relative frequency change is of the order of 0.1 %. So it's small, but measurable.

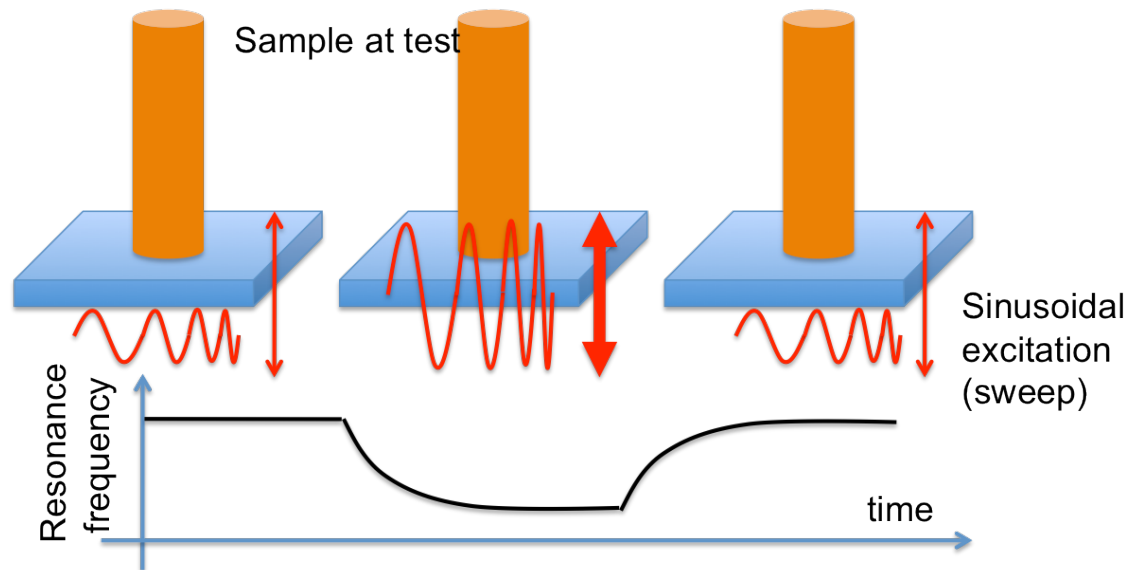


FIGURE 1. Typical experiment of resonance frequency tracked while the level of solicitation is increased or decreased. The logarithmic decay, and logarithmic recovery of the initial eigen-frequency is the signature of slow-dynamics. These experiments were performed initially at LANL [1], all proper references will be found in [2].

These laboratory experiments have the advantage of being well controlled and easily reproducible. Nevertheless, they can hardly be performed on-site. The purpose of the present paper is to propose an alternative experimental strategy that allows on-site application on concrete structures, particularly in the view of civil engineering applications.

Recently, Lobkis and Weaver [3] used the Larsen effect (acoustic feed-back) to monitor the very slight change of the loop-frequency due to SD. In their experiment, the solicitation was a small ball drop impacting the sample at test. The apparatus was transportable and there was no longer need of destructive sampling to quantify the SD effect.

Another possible idea to monitor SD in concrete is to take advantage of the high diffusivity of the material at a few 100 kHz. Indeed, above 100 kHz, the ultrasonic wavelength is smaller than the size of the heterogeneities (gravel, sand) and the ultrasound is multiply scattered by the medium [4]. Fig. 2 displays a typical waveform collected through a ~16 cm thick sample of concrete. The diffusion (or multiple scattering) regime can be characterized by the following features:

- The direct wave is highly attenuated (some times no more visible)
- Conventional imaging techniques, based on direct or simple scattering assumptions fails
- Onset of late arrivals constituting the coda.

The word “coda” has been recently inherited from the seismological community, where it refers to the tail of the seismograms after an earthquake. These late arrivals are constituted by the interference of various waves trajectories (see inset of Fig. 2). Because of the

complexity of the material, it is hardly possible to describe in details the phase and amplitude of coda waves, which might appear as the result of a random process. Nevertheless, the average intensity of the wave follows the diffusion equation, which is a deterministic (and easy-to-compute) equation. A considerable advantage of coda waves relies on the very high sensitivity to weak perturbations in the medium. After a very small perturbation, the waveforms can be either stretched in time, decorrelated, or both. These two effects are discussed in the next section.

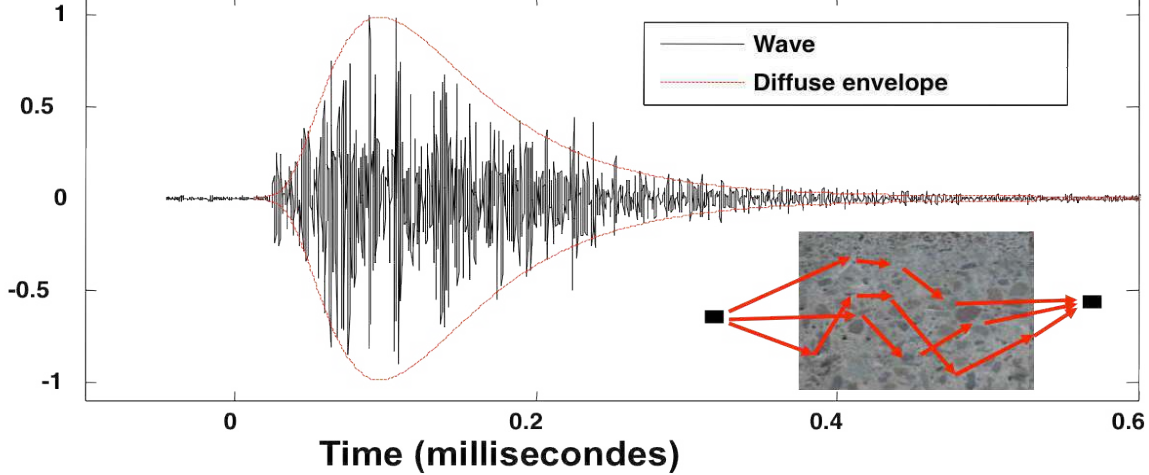


FIGURE 2. Full ultrasonic waveform (pressure in arbitrary unit) transmitted through 16 cm of concrete. The central frequency is 250 kHz (100% bandwidth). The effect of scattering is to 1) attenuate the direct ballistic wave, and 2) generate late arrivals constituting the ultrasonic coda. The envelope is well fitted by the diffusion equation (red broken line). Inset: concrete includes millimetric and centimetric heterogeneities.

CODA WAVE INTERFEROMETRY (CWI) AND DIFFUSE ACOUSTIC WAVE SPECTROSCOPY (DAWS)

Two categories of changes can be detected in the coda:

Coda Wave Interferometry

The first change in the waveform is related to a global evolution of the elastic modulus of the material, which leads to a change in the acoustic shear and compressional wave velocities. In the acoustic approximation (scalar field), this velocity change dV mainly results in a dilation of the waveform along the time axis: if the velocity increases (resp. decreased), the waveforms are contracted (resp. delayed) in time. This corresponds to stretching the time-axis by a factor $1+dV/V$. At first order, the waveform undergoes the following evolution: $\varphi(t) \rightarrow \varphi(t(1+dV/V))$. This idea forms the basis of Coda Wave Interferometry, initially developed in seismology and rock physics [5-6], which has also been applied more recently to thermal or stress changes in concrete [7-9].

In order to track the relative velocity change between the initial state A and the final state B , the final waveform $\varphi_B(t)$ is interpolated at times $t(1+\varepsilon)$ and the correlation coefficient with the initial waveform $\varphi_A(t)$ is evaluated:

$$CC(\varepsilon, t) = \frac{\int_{t-T/2}^{t+T/2} \varphi_A(u) \varphi_B(u(1+\varepsilon)) du}{\sqrt{\int_{t-T/2}^{t+T/2} \varphi_A^2(u) du \int_{t-T/2}^{t+T/2} \varphi_B^2(u) du}} \quad (1)$$

This calculation is performed for various stretching factors. The stretching factor that corresponds to the actual relative velocity change in the medium maximizes the correlation coefficient (1). More details about signal processing can be found in Ref. [10]. Of course in elastic heterogeneous materials, the scalar field assumption is basically not valid. Nevertheless, after sufficient scattering of the wave on different heterogeneities, the waves have been converted to all modes of propagations and have reached a state of statistical equilibrium called the equipartition [11]. In this equipartition regime, equation (1) applies.

Diffuse Acoustic Wave Spectroscopy

In many cases, the assumption that the waveforms are just stretched in time is wrong. In particular, the stretching factor is not sensitive to a change of structure in the medium. In 90's, opticians and acousticians demonstrated that the random (Brownian) motion of fluidized particle could be tracked by the decorrelation of the diffuse waveforms [12]. Of course, in the case of concrete, heterogeneities do not move. Nevertheless, as the microstructure can evolve, wave trajectories can happen to change resulting in a decorrelation of the ultrasonic coda. From the maximum of correlation obtained for the actual relative velocity change dV/V , we define the decorrelation simply as $1-CC(dV/V, t)$.

Physical interpretation of CWI and DAWS

To conclude this part, CWI is a measurement of a relative velocity change averaged over all the volume of investigation of the diffuse ultrasounds. CWI reports on a global macroscopic quantity. DAWS is sensitive to a change in wave trajectory, corresponding to a change in microstructure, grain arrangements and contacts. These are therefore two quantities that are quite different in origin.

SLOW DYNAMICS ON MECHANICALLY DAMAGED CONCRETE

In the first experiment, reported in [13], we use two cylindrical samples of 16 cm in diameter and 30 cm in height. Two ultrasonic transducers are used: one as a source and one as a receiver. They are 10 cm apart. The transducers are glued onto the sample so that their positions (and coupling) remain constant during the experiment. The ultrasonic experiment was performed several months after casting the samples. We send a 80 V broadband ultrasonic impulse with frequencies ranging from 50 to 500 kHz. The signal measured by the receiver is amplified, digitized, and stored in memory. The acquisition is repeated at various times d ($d=0$ starts the experiment), over about 1 h. After some time, we drop a small metallic ball (30 g) from a height 1.38 m onto the top face of the sample. The impact is about 15 cm from the source and receiver. The evolution of dV/V as a function of d is displayed in Fig. 3 (top). Note that the ball impact occurs 270 s after starting the experiment. Before the impact, there is no relative velocity change, indicating that the medium is at rest. Immediately after the impact, the velocity is noticeably decreased. This velocity drop is principally due to a drop of rigidity of the material. Then, the material stiffness rises back toward its initial value. The elastic energy released to the sample is 0.4 J. Note that we observe no visible damage caused by this moderate impact. The possible temperature elevation of the sample due to the energy of the ball impact would be of the order of a few 10^{-5}°C (if any), which would result in a relative velocity decrease of the order of at most 10^{-7} (we take the value of -0.1 to -0.2% per $^{\circ}\text{C}$ for the thermal-velocity variations following data from [7]). We thus conclude that the relative velocity drop (and recovery) can not be solely associated to thermal effects.

The time evolution of the decorrelation as a function of d is also plotted in Fig. 3 (bottom). Again, the record is very stable before the impact. After the impact, the ultrasonic waveforms differ significantly from the (initial) reference waveform, then the decorrelation from the reference waveform decreases over several hundreds of seconds. This decorrelation corresponds to a feeble change in the scattering properties of the concrete sample, for instance a small rearrangement of contacts between grains.

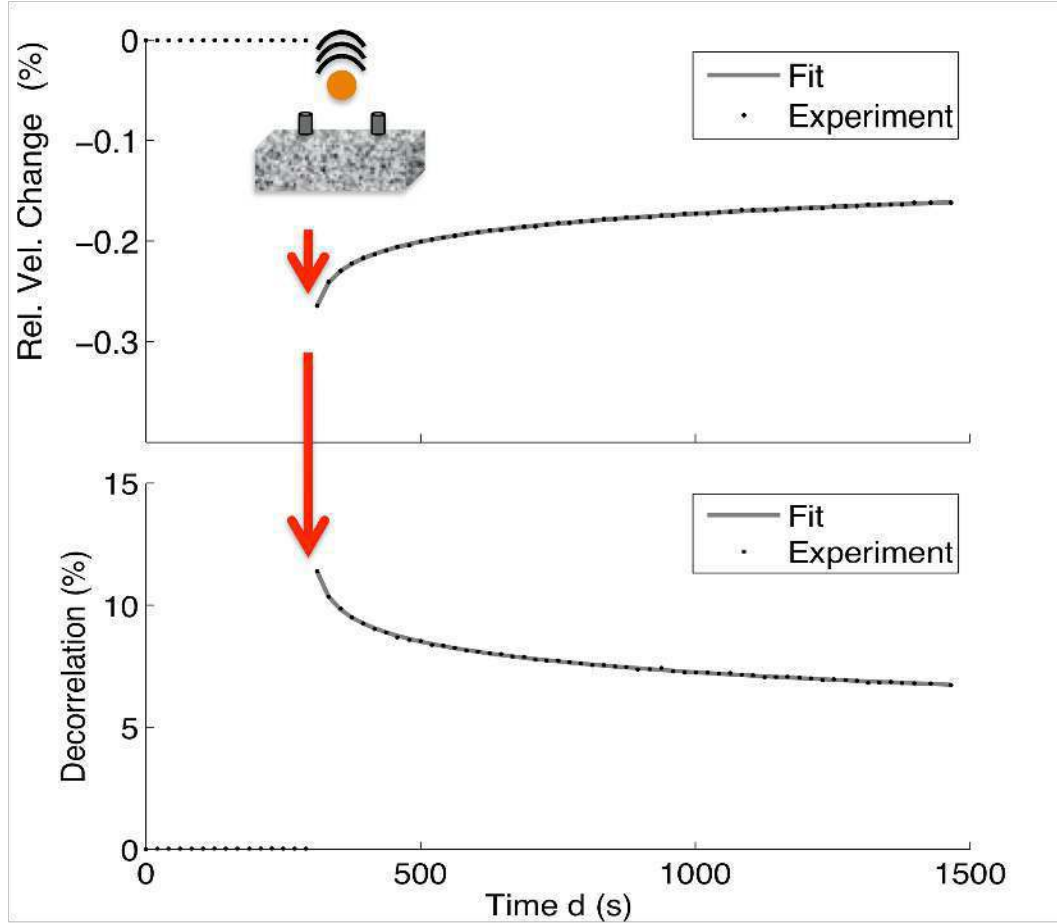


FIGURE 3. Relative velocity change dV/V (top) and decorrelation (bottom) of ultrasonic coda waves after the impact of a small ball (marked by the arrow). Figure is from [13]

Consider now a second block of concrete of similar constitution and of the same geometry. This second sample is damaged after undergoing a 30 MPa load. The experiment performed in the previous section is reproduced on both samples using the same protocol (but the height of the fall is decreased compared to previously), and data are processed in the same time window and frequency range. Resulting decorrelations are plotted in Fig. 4. We observe that damage increases considerably the amplitude of change in the material, and thus, the absolute decorrelation together with the speed of recovery of SD. Provided that the experimental protocol is rigorously similar from one site to another, this latter result suggests a possible route for on-site concrete damage assessment.

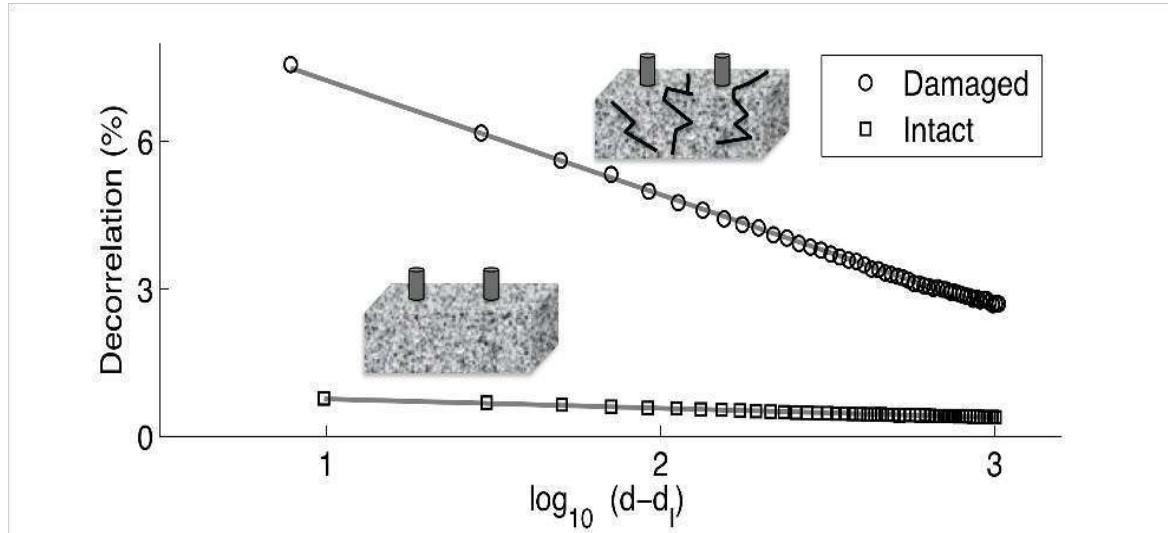


FIGURE 4. Slow Dynamics observed in damaged (top) and undamaged (bottom) samples of concrete. Note that the nature, geometry of the sample, along with the experimental procedure are rigorously similar in both cases, except that the damaged sample has undergone a 30 MPa load prior to the test. Fig. is from [13]

SLOW DYNAMICS ON THERMALLY DAMAGED CONCRETE

In order to confirm the sensitivity of SD to damage, en emphasize the particular sensitivity to microdamage, we reproduce the same experimental procedure on four similar samples of concrete having undergone a three-hour long thermal heating at different temperatures (20°C, 120°C, 250°C and 400°C, respectively). The sample sizes are 10x10x15 cm³. As a test, we drop a 460 g steel ball from a height of 25 cm. Ultrasonic waveforms are generated at a 1 MHz central frequency (broadband), and are acquired every five seconds, during about 40 minutes. Experiments were conducted under stabilized temperature and humidity. The relative velocity change, and recovery, is plotted on Fig. 5. As before, the first effect of the solicitation (the ball drop) is to decrease slightly the apparent stiffness of the material (relative velocity change of a few 10⁻⁴). What is also visible is that the higher the temperature, meaning the higher the thermal damage, the stronger SD. Note that these curves are linear regressions of the observed relative velocity changes, and that they have been adjusted to cross at a given time. So the main piece of information of these curves is certainly the slope, which basically appears to depend on micro-damage.

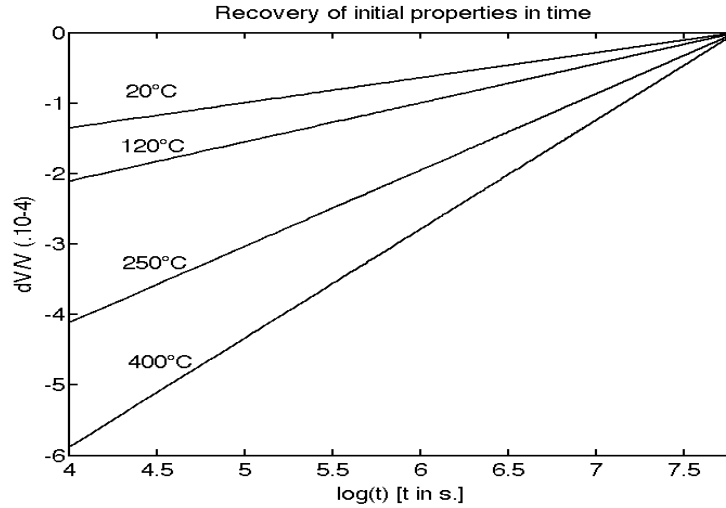


FIGURE 5. Relative velocity variation and velocity recovery after the moderate impact of a small ball on four different concrete samples. The samples have the same geometry, composition, and undergo exactly the same experimental procedure except the temperature at which they are exposed during 3h prior to the SD effect evaluation.

CONCLUSION

In this paper we reported on Slow Dynamics in concrete with diffuse ultrasound. To that end, we analyzed two different quantities: the relative velocity change (from Coda Wave Interferometry) and the decorrelation of the ultrasonic waveforms (using Diffuse Acoustic Wave Spectroscopy). The first technique yields a global observation of the macroscopic stiffness of the material at test, the second is more sensitive of changes in the microstructure. Both techniques confirms that a relatively small solicitation of the material results in intimate modification in the bulk of the material associated to a reduction of stiffness, followed by a log(time) recovery. In the first set of experiments, we compared SD effects in an intact and mechanically damaged concrete sample. Following rigorously the same experimental procedure, we demonstrate that SD is quantitatively more sensitive to damaged materials (larger change, larger recovery slope). Another set of experiments concerns four samples having undergone different thermal damage. Again, SD was found to monotonically depend on the level of damage of the sample, the more damage the larger the change, and the steeper the recovery slope.

The main advantage of diffuse waves tracked by CWI and DAWS is that they allow on-site measurement, including single side access to the structure. The presented results point out the possibility to on-site assessment of concrete. For a complete quantitative damage assessment, additional normalization actions have to be conducted. Also, as humidity directly affects SD, such quantitative damage assessment requires an a-priori knowledge of the moisture level of the concrete at test.

ACKNOWLEDGEMENTS

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