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# Effect of water saturation and porosity on the nonlinear elastic response of concrete

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ABSTRACT

Nonlinear interaction of a monochromatic elastic wave with a low frequency should be a good tool for non-destructive evaluation of existing concrete structures. Nonlinear indicators have already proved efficient in detecting global damage by exhibiting a significant sensitivity regarding classical linear ultrasonic methods like wave speed or attenuation. However, it is necessary to understand the influence of some structural parameters such as porosity, stress state, or water saturation on the nonlinear processes. In this way, a recent model containing all of these potential contributors is presented in this paper. It is sustained by nonlinear interaction experiments in impact mode. This method reveals a great potential for in situ measurements with a low frequency propagating into the whole structure. We make use of a calibrated concrete sample's series, conditioned at different water saturation states, to quantify the influence of water content and porosity on the nonlinear response of concrete.



## 1. Introduction

Nonlinear acoustics based methods offer promising means of on site non-destructive testing of concrete structures. Linear indicators, like wave speed or attenuation, have a limited sensitivity and significant variations appear late in the microstructure evolution process. Often, nonlinear based methods present a sensitivity more than one order magnitude greater than linear ones. This great sensitivity regarding damage is hopeful but the influence of structural and environmental parameters on the nonlinear elastic properties of concrete should be understood. In case of in situ measurements, there is a need to uncouple the influence of damage and the one of structural or environmental conditions on the nonlinear indicators.

Concrete is a naturally highly heterogeneous and microcracked media. It exhibits a strong nonlinear elastic response, which can be physically explained by the classical Landau and Lifschitz theory [1] and at different scales by dislocations, rupture and recovery of intergrain cohesive bonds, porosity, clapping contacts, etc. As a result, concrete and cement based materials fall into the nonlinear nonequilibrium class [2] known to exhibit "nonlinear nonclassical effects" [3] termed slow dynamic and anomalous fast dynamic [2].

Fast dynamic relates the quasi-instantaneous decrease of the elastic modulus with increasing wave amplitude. The fact that this decrease is unexpected regarding the classical Landau theory, and that these materials also exhibit hysteresis and end point memory effects [3], has been termed "anomalous" or "nonclassical". Slow dynamic relates the slow, logarithmic in time, recovery of initial elastic properties after the disturbance (order $10^3$–$10^4$ s in microcracked or damaged materials).

Van Den Abeele et al. show that this nonclassical nonlinear behaviour largely dominates the global nonlinear response of heterogeneous and microcracked materials such as concrete [4]. Thus, this behaviour can be phenomenologically described by a nonlinear elastic modulus [4,5]:

$$M = M_0[1-\alpha(\Delta\varepsilon + sign(\dot{\varepsilon})\varepsilon)], \tag{1}$$

where $M_0$ is the linear elastic modulus, $\alpha$ the nonlinear parameter, $\Delta\varepsilon$ the average strain wave amplitude, and the *sign* function equals $+1$ if the strain rate is positive and $-1$ if negative.

Nonlinear properties of materials can be non-destructively evaluated by harmonic generation, nonlinear wave interaction or nonlinear resonant ultrasound spectroscopy (NRUS). Nonlinear indicators reveal high potential for monitoring thermal [6], mechanical [7] damage, curing [8] of concrete or pre-stress state [9]. Nonlinear wave interaction is a good candidate for on site inspection, with a low frequency (LF) propagating in the whole structure. Moreover, this LF can be easily generated by a mechanical impact or by the natural solicitations of the structure like wind or traffic.

Assuming two harmonic sources, $S_1(t) = \Delta\varepsilon_1\cos(\omega_1 t)$ and $S_2(t) = \Delta\varepsilon_2\cos(\omega_2 t)$, in case of $\omega_2 \gg \omega_1$, the HF signal is amplitude modulated by the LF one. The resulting transmitted signal spectrum Fig. 1 provides means to extract the nonlinear $\alpha$ parameter [10] by the ratio of the fundamental amplitudes with the side lobes:

$$\alpha \propto \frac{A(\omega_2 \pm 2\omega_1)}{A(\omega_1)A(\omega_2)}. \tag{2}$$

This method is valid for monochromatic waves, and experimentally, the LF has to be sufficiently energetic to excite nonlinear phenomena.

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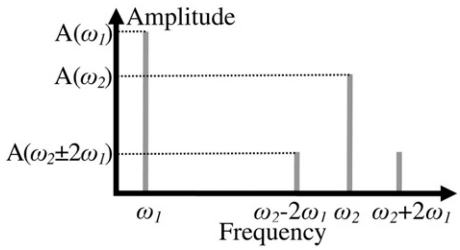


**Fig. 1.** Frequency spectrum result of nonlinear continuous wave's interaction.

Keeping in mind that the goal is on site inspection, generating high amplitude continuous waves seems to be difficult. Consequently, a simple apparatus will be employed with a mechanical impact that provides means to generate the high amplitude LF. However, the complexity of the resonant modes and the HF modulation deny using Eq. (2) to extract the nonlinear parameter (see Fig. 2). Van Den Abeele et al. [10] suggest and prove experimentally that the nonlinear parameter can be extracted not by the amplitude, but by the energy ratio:

$$\alpha \propto \frac{E_{SL}}{E_{LF}E_{HF}}, \tag{3}$$

where $E_{SL}$, $E_{LF}$ and $E_{HF}$ are respectively, the energy contained into side lobes, the LF, and the HF spectrum components.

Damage has a great influence on the nonlinear $\alpha$ parameter in concrete [6,7]. However, this large sensitivity may be also induced by environmental or structural parameters such as water saturation or porosity. In order to uncouple these potential contributors, a recent model containing all of them is described in the next section. Then, the experimental setup is presented and afterwards the study of these parameters' influence on the nonlinear response of concrete is achieved and discussed.

## 2. Model

Up to now, the most employed model was phenomenological, based on hysteresis description into the Preisach–Mayergoyz space [5]. The present model [11], quantitatively validated in sedimentary rocks, describes both slow and anomalous fast dynamic phenomena by the dependence of defect concentration on temperature and water saturation. Then, this concentration is related in the elastic modulus by:

$$M(c,\varepsilon,t) = M_0\left[1-f(s,T)\left(1+\frac{\delta c(\varepsilon,t)}{c_0}\right)\right], \tag{4}$$

where $M_0$ is the linear elastic modulus, $f(s,T)$ a function depending on water saturation ($s$) and temperature ($T$), $\delta c$ is the instantaneous defect concentration variation and $c_0$ the initial defect concentration. Under an alternative strain drive (frequency $\omega$ and amplitude $\Delta\varepsilon$), the

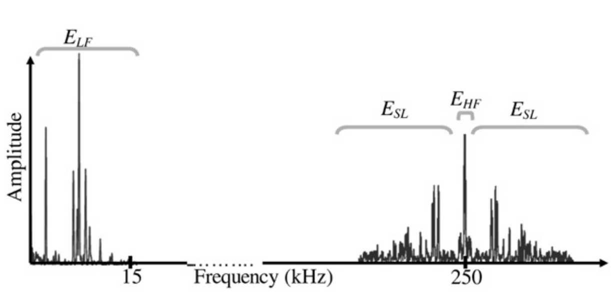


**Fig. 2.** Typical spectrum obtained in experiments.

defect concentration variation associated with the excitation can be written to the first order:

$$\delta c_\sigma = \frac{\upsilon c_0 M_0}{kT}\Delta\varepsilon \sin(\omega t), \tag{5}$$

with $k$ being the Boltzmann constant, $T$ the temperature, and $\upsilon$ the typical volume of a single defect. Authors [11] assume that both fast and slow dynamic effects result from the interaction of two elastic subsystems: a fast elastic subsystem governed by the $\lambda$ parameter in Eq. (6), and a slow elastic subsystem governed by the $\tau$ parameter in Eq. (6). It is interpreted by the defect concentration that evolves as a function of strain and time following a kinetic equation:

$$\frac{d(\delta c)}{dt} = -[\tau\theta(\delta c-\delta c_\sigma) + \lambda\theta(\delta c_\sigma-\delta c)](\delta c-\delta c_\sigma), \tag{6}$$

where $\lambda$ is the defect creation rate, $\tau$ the defect annihilation rate, and $\theta$ is the Heaviside step function. Solving this equation at each $t$ time allows estimating the instantaneous elastic modulus $M$ (Eq. (4)). The large disparity between slow and fast dynamic time scales makes $\lambda \gg \tau$, and thus implies that solutions of Eq. (6) are stable and tend to track the amplitude of $\delta c_\sigma$ [11].

The present study focuses on the fast dynamic effect that enables evaluating the nonlinear $\alpha$ parameter by the interaction of the HF continuous wave with the high amplitude LF. In the experiments, the typical wavelength of the LF is order 20 times larger than the HF one. Consequently, it can be reasonably assumed that experiments are performed in permanent regime ($\delta c \to \max(\delta c_\sigma)$). Therefore, assuming the temperature and water saturation are not influential during a single experiment, the elastic modulus can be written:

$$M = M_0\left[1-\frac{\upsilon M_0}{kT}\Delta\varepsilon\right]. \tag{7}$$

This equation demonstrates the analogy between the phenomenological model [5] and this one [11] (see Eq. (1)). The nonlinear $\alpha$ parameter can also be expressed:

$$\alpha = \frac{\upsilon M_0}{kT}. \tag{8}$$

Measuring the nonlinear $\alpha$ parameter of concrete samples for varying water saturation states will make possible the $f(s,T)$ function (Eq. (4)) determination. The next section presents performed experiments, results, and comments.

## 3. Experiments

To study the influence of porosity and water saturation on the nonlinear behaviour of concrete, a battery of measurements is performed on a concrete sample ($50\times25\times12$ cm$^3$) series with a water cement ratio varying from 0.3 to 0.8 conditioned at 0, 40, 60, 80 and then 100% saturation. Five series of six identical samples are studied. All samples of the same series have the same water cement ratio (w/c) and composition. First, every sample is conditioned at 0% water saturation in a steam room at 80 °C during months with a very slow increase then decrease in temperature. Then, they are conditioned at 100% by immersing samples in water. Finally, a part of each series is conditioned at 40, 60 or 80% saturation in a carefully controlled atmosphere.

The experimental setup Fig. 3 consists of a monochromatic HF wave (250 kHz) transmitting through the sample. The LF wave is generated by the impact of a steel ball (24.8 g) unhanded from a constant height (20 cm). The resulting LF signal is recorded and synchronizes the acquisition.

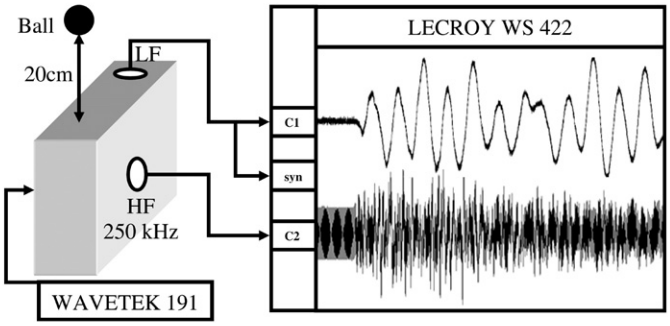


**Fig. 3.** Experimental apparatus.

Van Den Abeele et al. [10] suggest estimating the energies by a time frequency analysis (Fig. 4a). Recorded signals have a 200,000 points length with a sampling frequency of 10 MHz. A sliding Blackman time window of 0.8 ms is used with a time step of 0.3 ms. In view of increasing frequency resolution, the power spectrum is obtained by a chirpZ transform (See [7] for more details) instead of standard FFT. The HF frequency spectrum is normalized with respect to the HF amplitude assumed to be a constant. The SL energy is estimated all around the 250 kHz spectrum component so as to take into account all the energy contained in the side lobes. The energies of the side lobes ($E_{SL}$) and of the low frequency ($E_{LF}$) are extracted in each time window. We then plot $E_{SL}$ in function of $E_{LF}$ (Fig. 4c). The signal processing is illustrated Fig. 4b. The analysis stops when the LF signal reaches noise level. The nonlinear parameter is obtained by the slope of the fitted line (Fig. 4c). The determination coefficient ($R^2$) of this fitting has a mean value of 0.84 over all experiments. The time frequency image (Fig. 4a), is obtained by a reduced time step (0.03 ms). We show it to illustrate the signal processing method and the decay of the side lobes and the low frequency in time after the impact but not used in this form for calculation.

Note that the resulting nonlinear parameter is not an absolute value, and depends on the transducers. Nevertheless, the same transducers are employed during experiments. Thus, the obtained values are comparable to each others, obtained in the same manner.

Each sample is conditioned at 0 then 100% water saturation. That is not the case of intermediate values for which only a portion of each series is conditioned at 40, 60 or 80%. For that reason, the influence of water cement ratio on the nonlinear $\alpha$ parameter is studied for these extreme water saturation states (see Fig. 5).

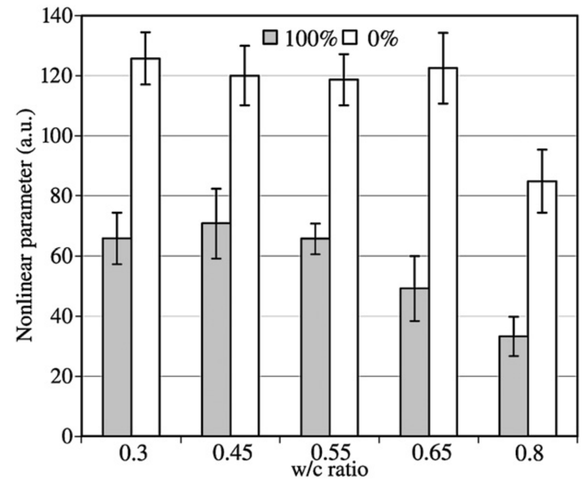


**Fig. 5.** Evolution of nonlinear $\alpha$ parameter as a function of w/c ratio for 0% (white) and 100% (grey) water saturation.

Two essential observations appear. The first is that porosity rate (w/c) does not seem having a notable influence on the nonlinear parameter into the usual w/c range (0.3<w/c<0.65 or 12.5<porosity in %<16). The second one is that water saturation has a large influence on the nonlinear parameter, with a mean decrease of 102% between dried and wetted state.

The limited influence of porosity rate allows averaging the nonlinear parameter values of every sample over each saturation state, in the common w/c range. The result obtained in the full water saturation range is plotted in Fig. 6.

There are few measurements of the nonlinear $\alpha$ parameter for varying water saturation states in the literature [12,13], and none to our knowledge in concrete and cement based materials, meaning these values are the first reported for these materials. Without reference results and with the purpose of optimising the model, experimental points (♦ in Fig. 6) are fitted with an exponential type function (solid curve in Fig. 6). Experiments were conducted at constant temperature, so the $f$ function (Eq. (3)) can be written as $f(s,T=cst)=K\exp(-2.3s^3+4.65s^2-3s)$, with $s$ being the water saturation ($0<s<1$). These experiments provide

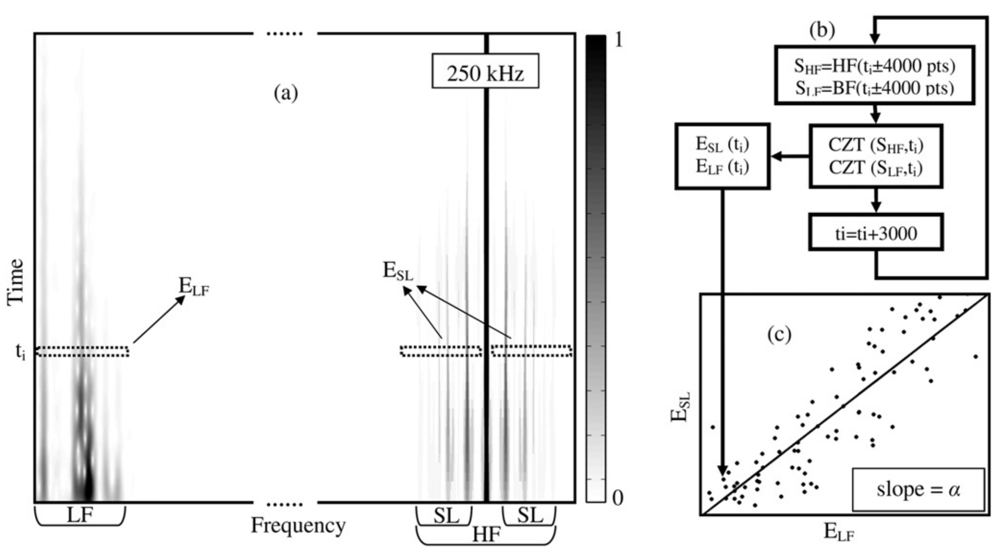


**Fig. 4.** Illustration of the signal processing method used to evaluate the nonlinear parameter. (a) Time frequency analysis. (b) Signal processing algorithm and (c) extraction of the nonlinear parameter for a concrete sample conditioned at 0% (log scale). Note that the frequency scale is not the same for the HF and LF components. The LF frequency axis has been stretched in order to clearly show the resonant modes.

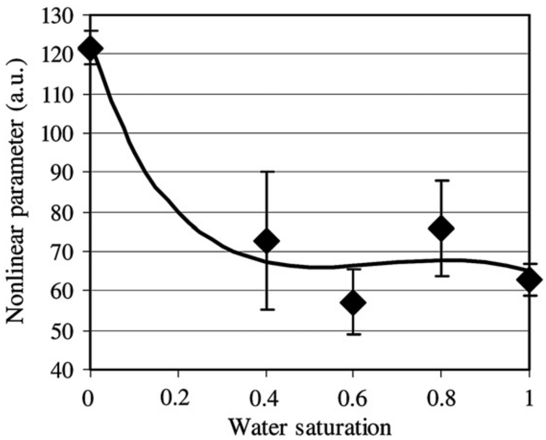


**Fig. 6.** Evolution of the nonlinear $\alpha$ parameter with water saturation ($0<s<1$). ♦ Present experimental values of the nonlinear parameter, error bars are the associated uncertainty. The solid line is the fit of experiments ($f(s,T=cst)$ function).

relative values, so $K$ is a constant to be determined by a reference measurement. The determination coefficient of this fitting is $R^2=0.94$.

## 4. Discussion

The sudden decrease of the nonlinear $\alpha$ parameter from 0% saturation is qualitatively equivalent to observations made in chalk [12] but very different from those made in rocks such as sandstone or limestone [12,13]. As for rocks, in the low saturation range (up to 20%), authors assume that the increase of the nonlinear parameter is due to solid–fluid interactions. In the latter saturation range, capillarity condensation dominates.

This physical interpretation, valid for rocks with small pores (typically $<10$ µm for sandstone), does not hold in concrete. The porosity scale is much larger and varies from nano (smallest pores) to millimetre (microcracks). Moreover, in intact concrete, "natural" microcracks are located in mortar or at the aggregate/mortar interface but not into aggregates. Thus, it is not surprising that the evolution of the nonlinear behaviour of concrete is different from rocks.

Physically, we posit that the abrupt decrease of the nonlinear parameter in the low saturation range may be due to larger porosities. Dried rough contacts are very nonlinear and it can be presumed that like for granular media [14], a small quantity of fluid added is sufficient to greatly modify the mechanical behaviour. Water lubes scrapping microcracks, and as a result, the nonlinear behaviour falls. In the latter saturation range, like for rocks [13], the capillarity condensation phenomenon dominates in the smallest pores. These results show that in the typical w/c range, it is not the rate but the size of porosities that seems to manage the nonlinear response of concrete. This is in accordance with the presented modelling, where the influential parameter is $\upsilon$ (Eq. (5)), the typical volume accounting by a single defect.

## 5. Conclusion and prospects

A promising method, with a high potential for on site inspection, is presented to extract the nonlinear parameter of concrete. The poor influence of porosity rate on the typical w/c range is shown and the influence of water saturation is quantified. A recent model that describes the influence of water saturation on the nonlinear response of concrete is presented and optimised.

Regarding the evolution of the nonlinearity with water saturation from 20% to 100%, the nonlinear parameter can be considered as constant in this range. As concrete structures are exposed to atmospheric conditions, between 30% and 100% of water saturation, nonlinear acoustics should not be used for water saturation characterization. However, this insensitivity makes this method a better candidate to process damage characterization.

Future research will be aimed at studying the influence of some concrete pathologies such as carbonization and chlorination on the nonlinear response of concrete.

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## References

[1] L.D. Landau, E.M. Lifshitz, Theory of Elasticity, Pergamon Press, New York, 1959.
[2] P.A. Johnson, Nonequilibrium nonlinear-dynamics in solids: state of the art, in: P.P. Delsanto (Ed.), Universality of Nonclassical Nonlinearity: Applications to Non-Destructive Evaluations and Ultrasonics, Springer, New York, 2006, pp. 49–69.
[3] P.P. Delsanto, M. Scalerandi, Modeling nonclassical nonlinearity, conditioning, and slow dynamics effects in mesoscopic elastic materials, Phys. Rev. B 68 (2003) 064107–064116.
[4] K. Van Den Abeele, J. Carmeliet, J. TenCate, P.A. Johnson, Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage. Part II: single-mode nonlinear resonance acoustic spectroscopy, Res. Nondestruct. Eval. 12 (2000) 31–43.
[5] R.A. Guyer, P.A. Johnson, Nonlinear mesoscopic elasticity: evidence for a new class of materials, Phys. Today 52 (1999) 30–35.
[6] C. Payan, V. Garnier, J. Moysan, P.A. Johnson, Applying nonlinear resonant ultrasound spectroscopy to improving thermal damage assessment in concrete, J. Acoust. Soc. Am. 121 (4) (2007) EL125–EL130.
[7] K. Warnemuende, H.C. Wu, Actively modulated acoustic nondestructive evaluation of concrete, Cem. Concr. Res. 34 (2004) 563–570.
[8] J.C. Lacouture, P.A. Johnson, F. Cohen-Tenoudji, Study of critical behavior in concrete during curing by application of dynamic linear and nonlinear means, J. Acoust. Soc. 113 (2003) 1325–1332.
[9] C. Payan, V. Garnier, J. Moysan, P.A. Johnson, Determination of third order elastic constants in a complex solid applying coda wave interferometry, Appl. Phys. Lett. 94 (2009) 011904.
[10] K. Van Den Abeele, et al., Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS), NDT E Int. 34 (2001) 239–248.
[11] O. Vakhnenko, V. Vakhnenko, T.J. Shankland, Soft-ratchet modeling of end-point memory in the nonlinear resonant response of sedimentary rocks, Phys. Rev. B 71 (2005) 174103.
[12] P.A. Johnson, B. Zinszner, P. Rasolofosaon, F. Cohen-Tenoudji, K. Van Den Abeele, Dynamic measurements of the nonlinear elastic parameter $\alpha$ in rock under varying conditions, J. Geophys. Res. 109 (2004) B02202.
[13] K. Van Den Abeele, J. Carmeliet, P.A. Johnson, B. Zinzsner, Influence of water saturation on the nonlinear mesoscopic response of earth materials and the implications to the mechanism of nonlinearity, J. Geophys. Res. 107 (B6) (2002) 2121.
[14] T. Brunet, "Sound propagation in dry and wet granular materials," PhD thesis, Université de Marne la Vallée, France (2006).