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Title: Addressing Facility Needs for Concrete Assessment Using Ultrasonic Testing: Mid-year Report

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Addressing Facility Needs for Concrete Assessment Using Ultrasonic Testing: Mid-year Report

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign
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SUMMARY

The *UFD Gap Analysis to Support Extended Storage of Used Nuclear Fuel* (June 30, 2011) emphasizes the need for the development of monitoring techniques and technologies for dry storage cask materials. A **high priority** is given to the development of "*systems for early detection of confinement boundary degradation.*" This requires both new techniques for monitoring and inspection, as well as new measurable parameters to quantify mechanical degradation. The use of Nonlinear Elastic Wave Spectroscopy (NEWS) has been shown to provide sensitive parameters correlating to mechanical degradation in a wide variety of materials. Herein we report upon recent research performed to address the high priority of concrete degradation using a selection of these techniques and compare to a ASTM standard ultrasonic technique. Also reported are the near term plans to continue this research in the remaining FY and into the coming years.

This research was conducted at Los Alamos National Laboratory (LANL) in the Acoustics Lab of the Geophysics group in the Earth and Environmental Sciences division, and in collaboration with the Laboratory for Nondestructive Evaluation at the University of the Mediterranean (Aix en Provence, France) and the Electrical Power Research Institute (EPRI).

CONTENTS

FIGURES

TABLES

ACRONYMS

NDE – Nondestructive Evaluation
NEWS – Nonlinear Elastic Wave Spectroscopy
NL – Nonlinear
NRUS – Nonlinear Resonant Ultrasound Spectroscopy
RUS – Resonant Ultrasound Spectroscopy
SSM – Scaling Subtraction Method
TOF – Time-of-flight
TR – Time Reversal
TREND – Time Reversal Elastic Nonlinearity Diagnostic
UFD – Used Fuel Disposition

USED FUEL DISPOSITION/STORAGE R&D ADDRESSING FACILITY NEEDS FOR CONCRETE ASSESSMENT USING ULTRASONIC TESTING: MID-YEAR REPORT

1. INTRODUCTION

In the context of license renewal in the field of nuclear energy, maintaining in service and re-qualifying existing concrete structures for ten years is a great challenge. For ecologic, economic and societal reasons, replacing a structure is often complicated Thus, increasing the safety and anticipating concrete degradation through the use of a powerful tool able to characterize concrete quality as its main function should be welcome. Many Non-Destructive methods such as thermography, radiography, electrical resistivity, radar, etc. provide information about the state of the concrete but the only one which is directly related with concrete mechanical characteristics is acoustics. Standard methods (ISO 1920-7; ASTM C597 - 09) such as pulse velocity have a poor sensitivity with regard to damage. Thus, taking into account measurement uncertainties, when this indicator crosses the detection threshold, the mechanical properties of concrete are substantially degraded. In addition, these methods, based on low frequency wave propagation, cannot provide information about the presence of a few centimeter scale localized defect. Developments in the field show that the indicators issued from the nonlinear wave propagation allow to considerably decrease the detection threshold in homogeneous materials and recently in concrete and cement based materials.

The objective of this research project was to determine the feasibility of using an NDE technique based on non-linear ultrasound for determining the depth and degree of micro-cracking in the near surface of concrete and to assess the degree of sensitivity of such technique. This objective is reached by the means of combining linear and nonlinear measurements, associated with numerical simulation. We first study the global effect of thermal damage on concrete's linear and nonlinear properties by resonance inspection techniques. We show that standard pulse wave speed techniques are not relevant to extract mechanical properties of concrete. The high sensitivity of measured nonlinearity is shown and serves as a validation tool for the rest of the study, i.e., probing the material nonlinearity at various depths through the use of Time Reversal Elastic Nonlinearity Diagnostic (TREND). The basic idea of probing the material nonlinearity at various depths by changing the frequency is validated by exhibiting a similar trend as nonlinear resonance measurements. We address at the end of this report, the potentialities of applying these procedures to real concrete structures.

As the results of the studies have been presented recently at the European acoustics conference “Acoustics 2012” in Nantes, France and can be found in detail in the prepared proceedings papers, this report will merely highlight the results. Full details can be found in the proceedings papers, which are attached as appendices.

2. Samples Used in Studies

Concrete samples that will be studied are thermally damaged at different temperatures. There are 4 sets of 4 samples (Fig.1.a) of identical geometry (~10x10x5 cm^3) defined in Tab. 1.

Table 1. Sample Designations

Exposure temperature (°C) / Composition	Cement Paste	Mortar	Ordinary Concrete	High Performance Concrete
20	CP20	M20	OC20	HPC20
120	CP120	M120	OC120	HPC120
250	CP250	M250	OC250	HPC250
400	CP400	M400	OC400	HPC400

These samples have been damaged following a controlled protocol (Fig.1.b) to avoid stress concentration phenomena expected to adjoin an undesired mechanical damage.

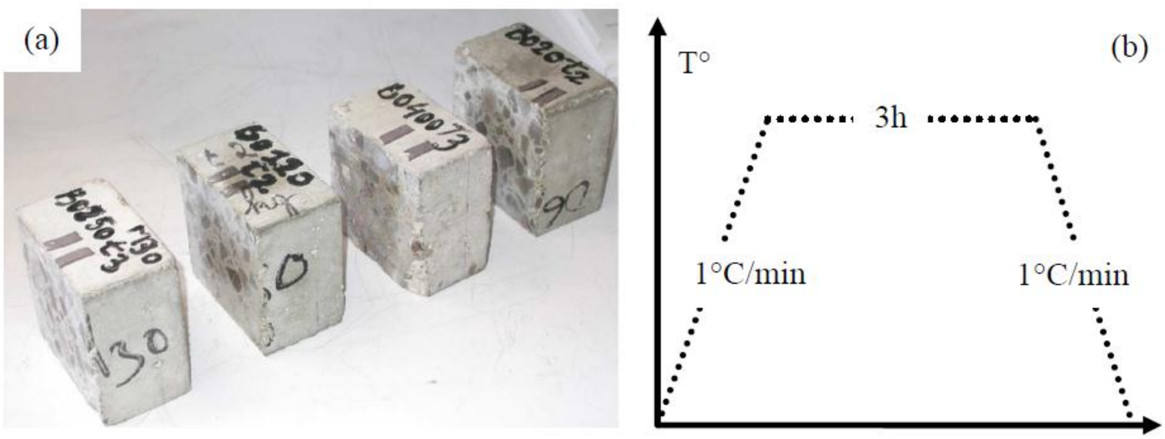

Figure 1. (a) Samples. (b) Thermal damage protocol

Note 1: These samples have been delivered from Aix en Provence (France) by UPS and hope that they have not been "damaged" during transportation. In addition, these samples are 8 years old, meaning that some chemical reaction such as carbonation might have occurred during their lifetime in storage. However, since they have been stored all together at the same place, we can reasonably expect that the effect would be the same for each sample.
Note 2: These samples are homogeneously damaged.
Note 3: Cement paste samples are completely cracked (macro cracks) due to thermal damage. The results may not be consistent, and thus these samples are not being studied.

3. Thermal Damage Process of Concrete

Concrete is a complex multiphase solid material composed, before curing, of anhydrous cement, aggregates, sand and water. Anhydrous cement is principally composed of Silica (SiO_2), Alumina (Al_2O_3), Lime (CaO) and Calcium Sulphate ($CaSO_4$). The aggregate size is generally between 3 and 25 mm. Cohesion of concrete is guaranteed by a water cement ratio (w/c) of typically $0.3<w/c<0.6$.

Chemical processes occur with heat generated during curing, producing an increase of porosity and micro-cracks.

In concrete the most brittle zone is the interface between aggregates and cement paste. This zone, namely the transition halo, is the most porous and crystallized one. The presence of silica fume and/or plasticizer in high performance concrete reduces the porosity in this zone. With increasing temperature, this zone is progressively degraded due to the evaporation of free water and mainly to the differential dilation between aggregates (expansion) and cement paste (shrinkage).

Chemical reactions occurring with thermal damage process of concrete is known and synthesized in Tab. 2. Evidence of cracking is obtained applying macrography (Fig. 2). It reveals two essential observations: (i) There is no preferential cracking direction validating our hypothesis of isotropic damage; (ii) Most cracks appear at the cement-aggregate interface (transition halo) and in the cement matrix but never inside the aggregates, following the chemical process described in Tab. 2 (the first aggregate transformation appears at 600 °C).

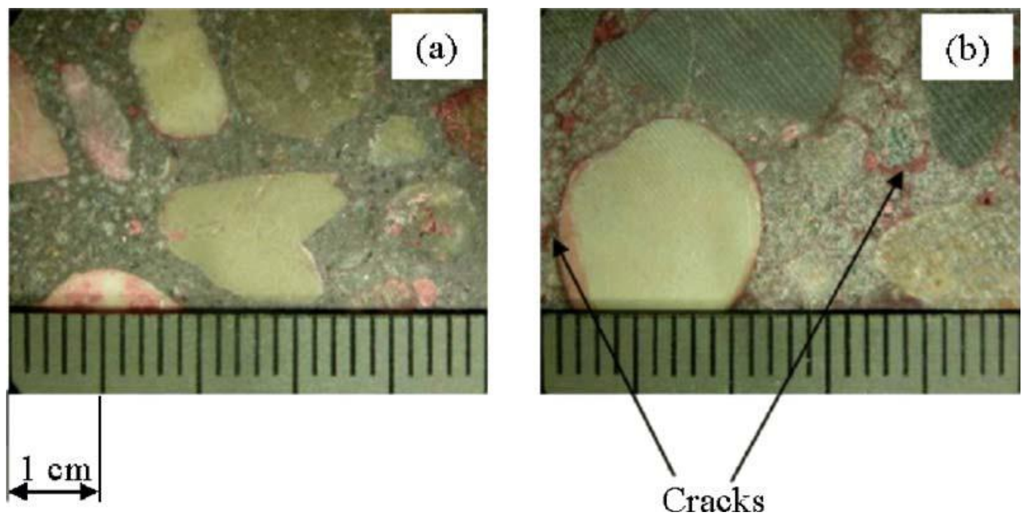

Figure 2. Macrography of intact sample (a) and thermally damaged sample (b).

Table 2. Chemical process occurring in concrete with increasing temperature. The top three rows are the temperature range studied here.

→105 °C	« Free » water evaporation
→300 °C	First step of dehydration. Breaking of cement gel and uprooting of water molecules into hydrated silicates.
400→500 °C	Portlandite decomposition : $Ca(OH)_2 \rightarrow CaO+H_2O$
600 °C	Structural transformation of quartz α into β - swelling of quartziferous aggregates
→ 700 °C	Second dehydration step : dehydration of Hydrated Calcium Silicates
→ 900 °C	Limestone decomposition : $CaCO_3 \rightarrow CaO+CO_2$
1300 °C	Aggregates and cement paste fusion

4. Experimental Techniques

Two linear ultrasonic techniques and two nonlinear elastic wave spectroscopy techniques were employed to determine elastic moduli and correlate to thermal damage level. For detailed experimental implementations of the above techniques, see the appendices. Below is a brief description of the four techniques, and the quantities which they each measure, followed by a summary of results.

4.1 Linear Ultrasonic Techniques

Standard ultrasonic techniques used are fundamentally *linear* techniques, referring to the fact that the waves are assumed to follow linear laws of physics, e.g., Hooke's Law. While there are many linear ultrasonic techniques that may be employed, two were selected for this study.

4.1.1 Pulse Velocity

Measuring the time-of-flight (TOF) of an acoustic pulse to traverse a known distance, thus determining wave speed, is a common ultrasonic technique. This method is an accepted technique for use in the nondestructive evaluation of concrete (ISO 1920-7; ASTM C597 - 09), where the pulse velocities, or wave speeds, are monitored for changes throughout a damage protocol. Two wave speeds are predominantly reported, shear (v_s) and compressional (v_p), though depending upon anisotropy, other wave speeds may be reported as well. In this report the concrete samples can be assumed to be isotropic, thus requiring the reporting of only two wave speeds, v_s and v_p. From the wave speeds, the elastic moduli can be calculated as $c_{11} = \rho v_p^2$ and $c_{44} = \rho v_s^2$, the compressional and shear moduli respectively.

4.1.2 Resonant Ultrasound Spectroscopy

Another linear ultrasonic technique is Resonant Ultrasound Spectroscopy (RUS). This technique employs the standing waves, otherwise referred to as resonances or modes of vibration, along with the dimensions, and mass to determine the elastic tensor of the material under test. The elastic tensor for an anisotropic system can consist of as many as 21 independent elastic moduli. Again, here the samples are sufficiently isotropic to reduce the independent moduli to two, c_{11} and c_{44}, the compressional and shear. The advantage to obtaining the elastic moduli through RUS over the TOF method above lies in the fact that the resonance of an object depends upon the entire bulk and can thus average over heterogeneities, where as TOF measurements can be adversely affected by localized heterogeneities, as well as by dispersion. While this is generally accepted to be true, RUS has not, until now, been used for measuring elastic moduli in concrete.

RUS also provides for the ability to quantify the intrinsic attenuation in a material. This linear quantity, often defined using the quality factor Q, is sometimes reported for the use of damage monitoring. When mechanical damage, e.g., micro-cracks, accumulate in a material the Q of that material is expected to decrease, indicating an increase in the attenuation.

4.2 Nonlinear Ultrasonic Techniques

Nonlinear ultrasonic techniques, broadly referred to as Nonlinear Elastic Wave Spectroscopy (NEWS) differ from standard, i.e., linear, ultrasound in that they utilize the amplitude dependent nature of the ultrasonic response. This style of measurement allows for the ability to deviate from linear assumptions to include nonlinear terms in otherwise linear relations, thus providing additional quantifiable parameters that are more sensitive to the presence of mechanical damage in solids. It should be noted that nonlinear techniques generally require higher amplitude excitations than linear techniques; though higher these amplitudes remain in the elastic regime and thus do not induce or further any mechanical damage.

4.2.1 Nonlinear Resonant Ultrasound Spectroscopy

Performing standard RUS measurements over a variety of amplitudes is referred to as nonlinear resonant ultrasound spectroscopy (NRUS). When performing NRUS measurements the focus is not the elastic tensor, as in linear RUS, but rather in the shift in resonance frequencies (and thus changes in elastic moduli) as a function of strain. These changes in moduli due to increasing strain indicate the presence and degree of damage in the material. The nonlinear parameter α, a higher order elastic constant, is proportional to the frequency shift Δf. Both α and Δf are commonly reported quantities from NRUS measurements

Alternatively, the nonlinear attenuation can also be quantified as $1/Q_{NL}$. This physically indicates the phenomenon in which change in strain is not directly proportional to the resulting response. This quantity and a Q_{eff}, an effective Q combining both Q and Q_{NL}, are sometime reported from NRUS measurements, however the frequency response parameters (α and Δf, above) are the more commonly reported values due to ease of extraction from the measurement.

4.2.2 Time Reversal Elastic Nonlinearity Diagnostic

The time reversal elastic nonlinearity diagnostic (TREND) combines the use of time reversal (TR), a method to focus wave energy in time and space, with NEWS techniques for the purpose of damage detection and imaging. As such, there are many nonlinear parameters that can be quantified. Here the scaling subtraction method (SSM) was used to extract a nonlinear elastic wave energy parameter. This metric was chosen for its ease of extraction from TREND data.

Due to the focusing abilities of TR, TREND provides a localized measurement. This allows for the compilation of successive TREND measurements at various positions to construct images of damaged regions. Alternatively the measurement location can be held fixed and the parameters of the TREND measurements be adjusted to penetrate more deeply, or shallowly, into the material, thus providing the potential to quantify penetrations depths of damage, a major concern in concrete structures.

4.3 Summary of Results

There are three main comparisons to be made in this study: 1) the comparison of the linear techniques to each other, 2) the comparison of nonlinear techniques to one another, and finally 3) the comparison of linear to nonlinear techniques.

4.3.1 Linear: TOF vs. RUS

As expected, the TOF measurements provide a different estimate of the elastic moduli than that from RUS. This can be seen in fig. 3. Also, note that when using the TOF technique, the frequency at which the measurement is conducted must be specified. Due to the dispersion in concrete choosing a different frequency can result in a different estimation of the elastic moduli. Without additional information, it is impossible to say which TOF result is correct. Contrary to this, RUS measures the frequency response for the modes of vibration. As these are determined by sample size, geometry density and elastic moduli, there is no difficulty in determining which value is the correct one. That is, RUS provides one set of moduli which best describes the elasticity of the system without the need to make a discrimination among used frequencies, making RUS a more robust technique.

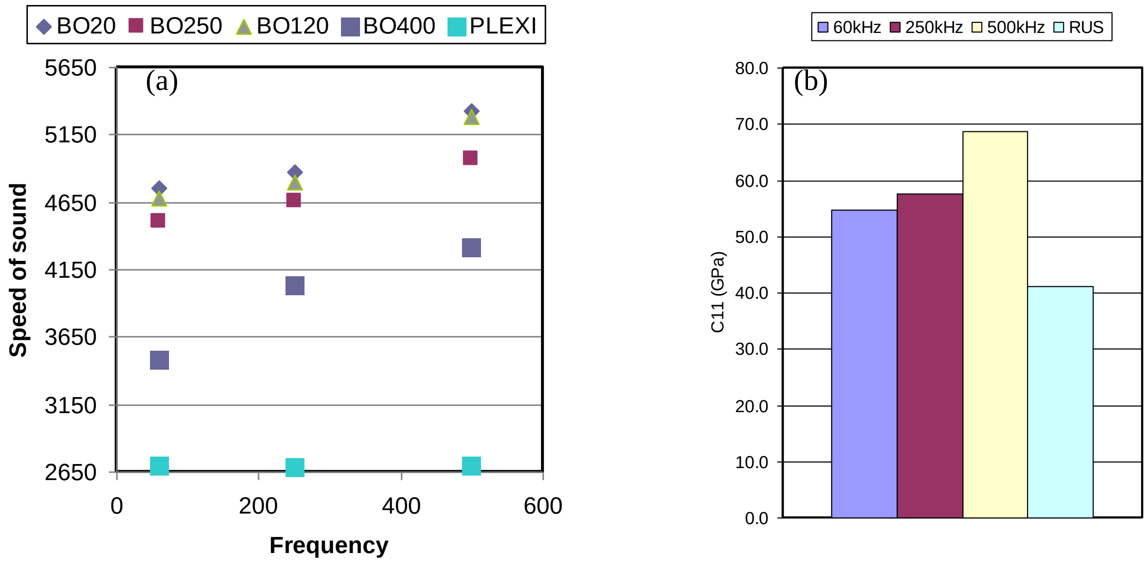

Figure 3. (a) Evolution of the compressional wave speed as a function of frequency in concrete samples. (b) Elastic constant derived from RUS and wave speed at various frequencies. All results shown for the ordinary concrete samples.

4.3.2 Nonlinear: NRUS vs. TREND

Comparing the two nonlinear techniques shows a remarkable agreement in the measured response (fig. 4). This is very encouraging for the use of TREND, which is a new and not widely accepted technique. As both techniques are equally sensitive to the presence of damage, choosing a technique to use for inspection can be done on a case by base basis as to which would be easier to employ in a particular instance. However, as the samples studied here there is no clear indication of which would be best for determining depth of penetration. It is expected that the localization and customization abilities of TREND would be beneficial for this application.

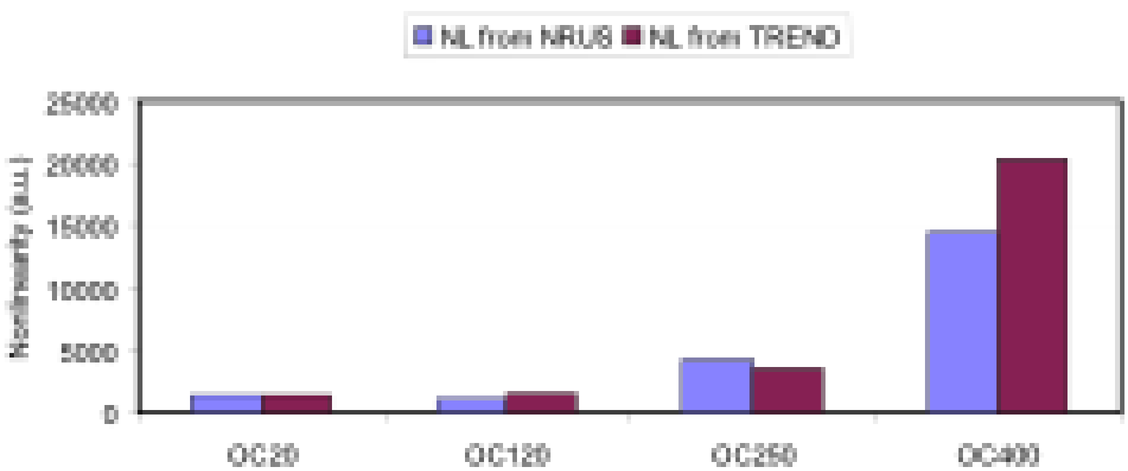

Figure 4. Comparison of nonlinear (NL) response as measured by NRUS (blue) and TREND (red) for ordinary concrete (OC).

4.3.3 Linear vs. Nonlinear

Currently accepted and standardized ultrasonic techniques for NDE of concrete are limited and exclusively linear in nature. Below, in fig. 5 (note the log scale), a comparison of a standard linear ultrasonic measurement (speed of sound, wave speed, as calculated from RUS) is compared to the nonlinear response (α as measured from NRUS). It is clear that in concrete, as in all other materials tested in this manner, that nonlinear parameters are much more sensitive to damage than the standard methods currently in use. This is true for all concrete samples studied here, i.e., OC, HPC, and M.

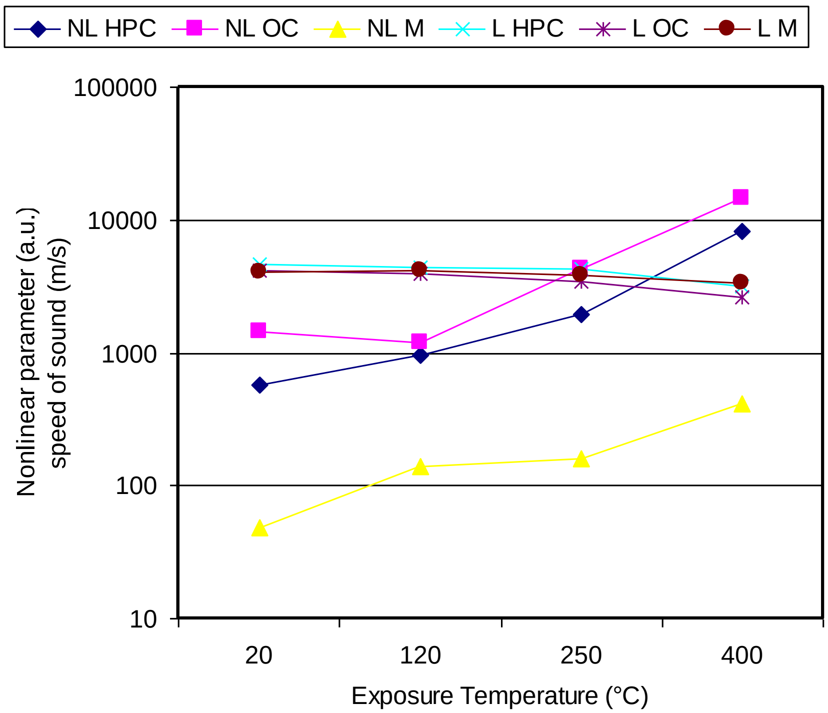

Figure 5. Compilation of linear (L: speed of sound) and nonlinear (NL: nonlinear α parameter) parameters as a function of thermal damage exposure.

5. Future Directions

The research described above is the initial step toward providing a next generation NDE diagnostic for concrete integrity to address facility needs in early detection of integrity reduction for advancing prognostic capabilities. To further this effort to a deployable tool there is still a series of tests that will need to be conducted and continued research, however, the current state of the art in nonlinear ultrasonic testing is sufficiently advanced to expect a TREND and/or NRUS based tool to be developed in the coming years.

During the remainder of FY12, a similar study, as described above, will be conducted on emulated freeze-thaw damage, a high priority failure mechanism for Storage R&D. This study will be conducted with a team of three advanced undergraduate/early graduate students as part of the LANL and UC Engineering Institute's Engineering Summer School (ESS). The project will include experimental, analytical and numerical components to work toward tool development. The samples to be conducted will be made in April 2012 and damaged in May using freeze-thaw cycles on wetted concrete to produce various, and controlled, depths of the damage layer, as opposed to the homogeneously thermally damaged samples used to date.

Other noteworthy developments include:

- Four manuscripts currently in preparation and intended for peer-reviewed journals.
- Special session on nonlinear NDE for NE applications to be held at the 17th International Conference on Nonlinear Elasticity in Materials (to be held July 2012 in Sicily, Italy).
- Application submitted to the Partnership University Fund (PUF), a French grant to facilitate collaboration of French Universities with U.S. institutions. Focus of project is NDE for NE applications.
- Invitation to collaborate with the concrete lab at EMPA (Zurich, Switzerland) on the general topic of concrete integrity.
- Work begun to acquire radiation-damaged concrete samples and/or conduct *in situ* testing of radiation-damaged concrete in a decommissioned LANL facility.

An end of year status report will be filed, wherein the progress of the ESS project will be reported and an update provided on relevant noteworthy accomplishments and/or activities.

Appendix A

Acoustics 2012 Proceedings I

Quantitative linear and nonlinear resonant inspection techniques for characterizing thermal damage in concrete

ACOUSTICS 2012

Quantitative linear and nonlinear resonant inspection techniques for characterizing thermal damage in concrete

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In the context of license renewal in the field of nuclear energy, maintaining in service and re-qualifying existing concrete structures for the period of long term operations is challenging. The integrity of concrete in the concrete pedestal and biological shield wall in nuclear plants remains unknown. These structures have been subjected to radiation and medium temperature for a long period of time. This paper aims at providing some quantitative information related to the degree of micro-cracking of concrete and cement based materials in the presence of thermal damage. We develop a methodology based on linear resonant ultrasound spectroscopy, numerical simulations and nonlinear resonant ultrasound spectroscopy to provide quantitative values of nonlinearity. We show the high sensitivity of derived nonlinearity to thermal damage and its correlation with the evolution of concrete microstructure.

1 Introduction

Mechanical resonance is a phenomenon that occurs when the wavelength λ corresponds to a characteristic dimension (or a multiple) of a sample. For simplification, we consider here a quasi-1D problem, a cylinder of length L with a Young's Modulus E. If this cylinder is driven at a specific frequency f0 for which the half wavelength equals L, the resonance is reached (Fig. 1).

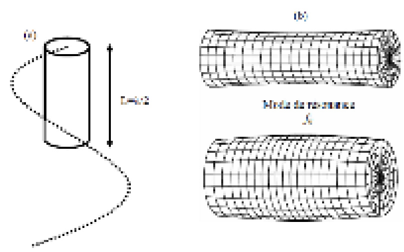


Figure 1: Resonance mode of a cylinder. (a) wavelength compared to the length of the sample. (b) resonance mode

As the speed of sound s is linked to the Young's modulus E as $s=\sqrt{E/\rho}$ and that $\lambda=s/f_0$, one can extract the relationship :

$$f_0 = \frac{1}{2L}\sqrt{E/\rho} \quad (1)$$

where ρ is the density. So, as the length and the density are known, by measuring the resonant frequency one can evaluate the elastic properties (E).

Based on this simple principle, but adapted to more complex 3D geometries, resonance inspection techniques are known and employed for years [1]. Resonant Ultrasound Spectroscopy (RUS) allows the material elastic properties to be determined accurately by non-destructive means. The input values are the sample geometry and the density. By exciting the sample in a large frequency range, one can extract the resonance peaks (experimentally measured values) corresponding to various eigenmodes. Then, by combining experimental and input values, an inversion algorithm provides the full elastic tensor of the sample. This can apply to any elastic material type (isotropic or anisotropic). RUS has been employed in various homogeneous materials and more recently in inhomogeneous ones such as rocks [2] cement [3]. However, this method has never been employed for concrete nor to detect damage. Our concrete samples have a finite geometry (parallelepiped) making the RUS method a perfect candidate to determine their linear characteristics.

Nonlinear Resonance Ultrasound Spectroscopy (NRUS) was developed at LANL in the 1990's. It exhibits a large sensitivity to damage in a wide range of micro-inhomogeneous materials for various application domains (concrete, rocks, damaged steel or aluminum components, damaged composite, bones, etc.). The nonlinear parameter is usually extracted by the slope of the line (Fig. 2) by

$$\frac{f - f_0}{f_0} = \alpha\Delta\varepsilon \quad (2)$$

where f_0 is the linear resonance frequency (low amplitude), f_i the resonance frequency when drive at the i_{th} amplitude, α the nonlinear parameter and Δε the strain amplitude. Since this method is applied to samples with appropriate geometry (cylinder with large aspect ratio), as the vibration mode along its height is very easy to detect, the measured vibration amplitude of the sample is proportional to the strain. However, for more complex geometry, this assumption does not hold because of the mode shapes complexity (Fig. 6). This is why we make use of numerical simulation that allows identifying a particular mode and so extract the strain values. The input values of numerical simulation are the elastic constants provided by RUS measurements.

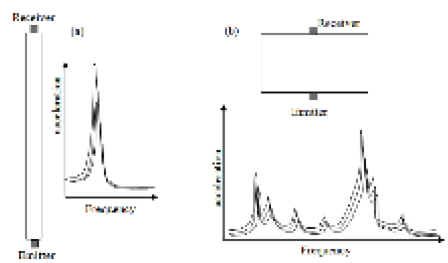


Figure 2: Resonance mode of a cylinder. (a) wavelength compared to the length of the sample. (b) resonance mode

It is important to notice that this procedure is followed in order to get quantitative values of nonlinearity, which has never been done yet for particular geometries. To detect damage, even qualitatively, these steps are not needed. This point is underlined at the end of the document.

The following sections describe RUS measurements, how these results are integrated to numerical simulations and NRUS results.

2 Thermal damage process of concrete

Concrete is a complex multiphase solid material composed, before curing, of anhydrous cement, aggregates, sand and water. Anhydrous cement is principally composed of Silica (SiO2), Alumina (Al2O3), Lime (CaO) and Calcium Sulphate (CaSO4). The aggregate size is generally between 3 and 25 mm. Cohesion of concrete is guaranteed by a water cement ratio (w/c) of typically $0.3<w/c<0.6$. Chemical processes occur with heat generated during curing, producing an increase of porosity and micro-cracks.

In concrete the most brittle zone is the interface between aggregates and cement paste. This zone, namely the transition halo, is the most porous and crystallized one. The presence of silica fume and/or plasticizer in high performance concrete reduces the porosity in this zone. With increasing temperature, this zone is progressively degraded due to the evaporation of free water and mainly to the differential dilation between aggregates (expansion) and cement paste (shrinkage).

Chemical reaction occurring with thermal damage process of concrete is known and synthesized in Tab. 1. Evidence of cracking is obtained applying macrography (Fig. 3). It reveals two essential observations: (i) There is no preferential cracking direction validating our hypothesis of isotropic damage; (ii) Most cracks appear at the cement-aggregate interface (transition halo) and in the cement matrix but never inside the aggregates, following the chemical process described in Tab. 1 (the first aggregate transformation appears at 600 °C).

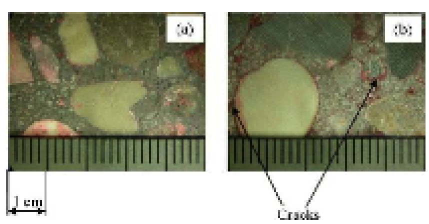


Figure 3: Resonance mode of a cylinder. (a) wavelength compared to the length of the sample. (b) resonance mode

Table 1: Chemical process occurring in concrete while increasing temperature. The top three lines are the temperature range studied here.

→105 °C	« Free » water evaporation
→300 °C	First step of dehydration. Breaking of cement gel and uprooting of water molecules into hydrated silicates.
400→500 °C	Portlandite decomposition : $Ca(OH)_2 \rightarrow CaO+H_2O$
600 °C	Structural transformation of quartz α into β - swelling of quartziferous aggregates
→ 700 °C	Second dehydration step : dehydration of Hydrated Calcium Silicates
→ 900 °C	Limestone decomposition : $CaCO_3 \rightarrow CaO+CO_2$
1300 °C	Aggregates and cement paste fusion

3 RUS measurements

Each sample is placed on a stand with various position to pick the entire set of resonance modes needed for the RUS inversion. One of the 3 transducers (Fig. 4) is driven by a sinusoidal voltage, onto a given frequency range, while the two others record the response. The sample is oriented in various positions in order to be able to pick each of the first 10 resonance frequencies. For this study, 10 resonant frequencies (Fig. 5) are used to get the linear elastic characteristics of the sample (i.e., compressional and shear moduli C11 and C44, which can be related directly to E and ν).

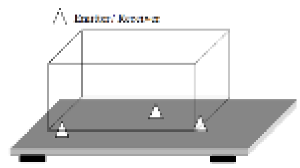


Figure 4: Resonance mode of a cylinder. (a) wavelength compared to the length of the sample. (b) resonance mode

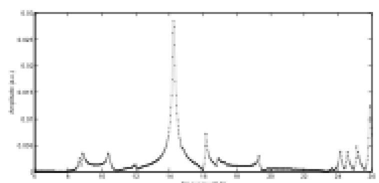
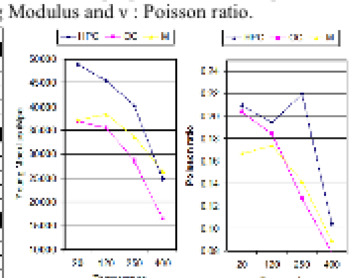


Figure 5: Resonance mode of a cylinder. (a) wavelength compared to the length of the sample. (b) resonance mode

The 10 firsts resonance frequencies determined, the inversion procedure provide the elastic characteristics given Table 2. These experiments have been performed and processed using the RITA software developed at LANL.

Table 2: RUS derived elastic properties of the samples. E : Young Modulus and ν : Poisson ratio.

	E (Mpa)	ν
HPC		
20	48400	0.23
120	45242	0.19
250	40159	0.22
400	24782	0.10
OC		
20	39912	0.20
120	35492	0.18
250	28966	0.12
400	16096	0.08
M		
20	37176	0.17
120	33834	0.17
250	32588	0.14
400	20260	0.09



These values highlight the effect of thermal damage on concrete with a decrease of elastic properties with increasing damage. As expected, High Performance Concrete have better mechanical properties than Ordinary Concrete and Mortar suffers in a lesser extent from thermal damage because of the absence of aggregates, and thus a transition halo. These results are in agreement with existing literature [4].

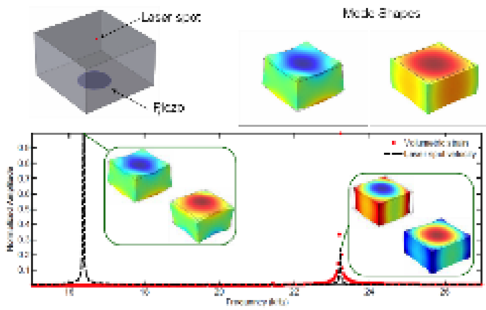


Figure 9: Numerical simulation of experiments.

One can realize that the highest velocity amplitude (black dashed curve) mode is a nearly zero volumetric strain (red dotted curve) amplitude mode because of the symmetry of the mode shape. The second mode, reaches a high strain amplitude with a low velocity at the top of the sample (laser spot location). The study of low volumetric strain mode may be of interest from a basic research point of view because of domination of shear effects, but this is not the purpose of this study. So, we select the "bulk mode" corresponding to an analogous mode as for cylinders (Fig. 1) that will allow obtaining quantitative values of the nonlinearity. Then, the same procedure is applied to each sample to get the absolute value of the volumetric strain so as we are able to link the measured velocity (laser) to the strain inside the sample.

With the mode selected, NRUS measurements are performed for each sample. The results are given in Figs. 10 to 12 for, respectively, Mortar, High Performance Concrete and Ordinary Concrete. The slopes of the lines are the nonlinear parameter α evaluated from Eq. 2.

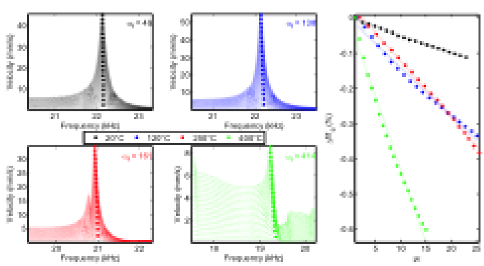


Figure 10: Mortar NRUS results.

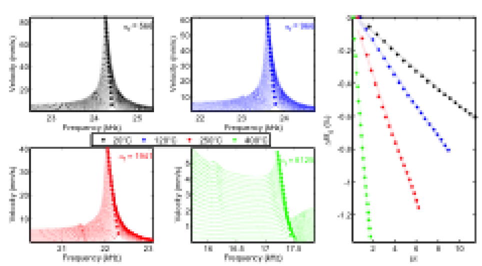


Figure 11: High Performance Concrete NRUS results.

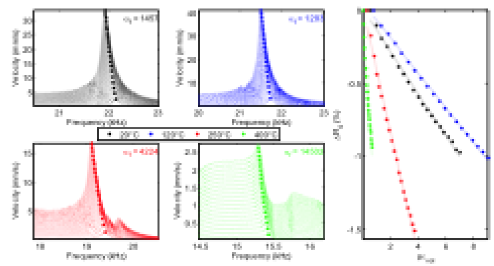


Figure 12: Ordinary Concrete NRUS results.

We can observe from these plots that 120°C and 250°C damaged Mortar samples have a similar nonlinearity, as well as 20°C and 120°C Ordinary Concrete ones. However, for each sample set, the variation amplitude is one order of magnitude (10 times higher at 400°C than 20°C). It is important to notice that without taking into account the true strain inside the sample, the net effect appears larger. This is explained by the decrease of the elastic properties that has to be taken into account. For a given amplitude level σ, as the modulus E decreases with damage, the strain ε inside the sample is higher (σ = E ε), so the slope decreases.

The linearity of the experimental system has been checked by applying NRUS to a known linear material (plexiglass) (Fig. 12) with the same geometry as the concrete samples and thus exhibiting the same resonance mode shapes. The lower frequencies of these modes simply indicate that the plexiglass is a softer material than the concrete.

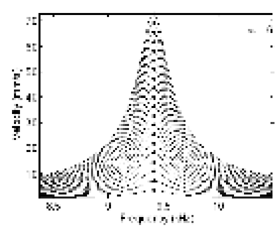


Figure 12: Plexiglass sample NRUS results

6 Summary-Conclusion

The compilation of linear and nonlinear results is given Fig. 13. The linear parameter chosen is the speed of sound calculated from RUS measurements. We use this linear indicator to compare with nonlinearity because the frequency shift, and so α, and speed of sound are comparable in terms of units. In addition, speed of sound is a standard NDT indicator. To compare with elastic modulus, further study on nonlinearity is needed to directly link the nonlinearity and the elastic properties change with increasing amplitude. Such a basic research topic is underway.

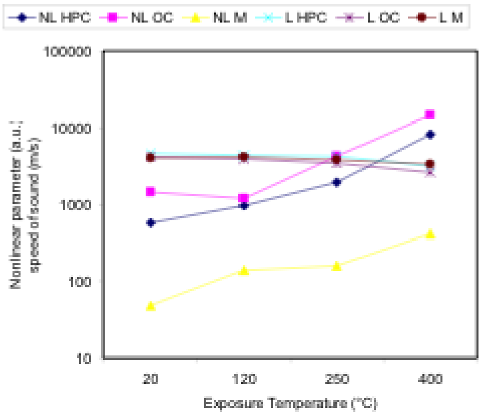


Figure 13: Compilation of linear (L : speed of sound) and nonlinear (NL : nonlinear α parameter).

As expected, these results reveal a great sensitivity (two orders of magnitude higher) of the nonlinear parameter to thermal damage as regarded with a standard linear NDT indicator (speed of sound). As stated in section 2, most of the damage comes from the transition halo (aggregate/cement interface). Thus, while there is no aggregate inside, the Mortar samples are less nonlinear than the other concrete samples. Of all the samples, Ordinary Concrete is more nonlinear than High performance concrete due to the presence of silica fume and plasticizer in HPC that reduces the porosity at the transition halo.

This is the first time in the literature that the combination of linear measurements (RUS) with numerical simulation and nonlinear measurements (NRUS) allows to quantitatively evaluate the nonlinear behavior of materials. It is applied to study the effect of thermal damage in concrete with results correlated to the evolution of the microstructure.

References

[1] Migliori A., John L. Sarrao, Resonant ultrasound spectroscopy: applications to physics, materials measurements, and nondestructive evaluation, Wiley, 1997

[2] Ulrich, T.J., McCall, K.R., and Guyer, R.A., Determination of elastic moduli of rock samples using resonant ultrasound spectroscopy, J. Acoust. Soc. Am. 111(4), 1667-74 (2002)

[3] Wu W. et al., Measurement of Mechanical Properties of Hydrated Cement Paste Using Resonant Ultrasound Spectroscopy, Journal of ASTM International, Vol. 7, No. 5 (2010)

[4] Maréchal, JC. Variations of the modulus of elasticity and Poisson's ratio with temperature. In Concrete for Nuclear Reactors, ACI SP-34, 1, 495-503 (1972)

[5] Zardan J.-P., C. Payan, V. Garnier and J. Salin, Effect of the presence and size of a localized nonlinear source in concrete, Journal of the Acoustical Society of America 128 (1), EL38-EL42 (2010)

[6] Antonaci P, C L E Bruno, A S Gliozzi, M Scalerandi, Monitoring evolution of compressive damage in concrete with linear and nonlinear ultrasonic methods, Cement and Concrete Research 40 (7), 1106-1113 (2010)

[7] Payan C., V. Garnier and J. Moysan, Effect of water saturation and porosity on the nonlinear elastic response of concrete, Cement and Concrete Research 40, 473–476 (2010)

[8] Payan C., V. Garnier, J. Moysan and P. A. Johnson, Applying nonlinear resonant ultrasound spectroscopy to improving thermal damage assessment in concrete, Journal of the Acoustical Society of America 121 (4), EL125-EL130 (2007)

[9] Bouchaala F., C. Payan, V. Garnier and J.P. Balayssac, Carbonation Assessment in Concrete by Nonlinear Ultrasound, Cement and Concrete Research 41, 557–559 (2011)

[10] Kodjo A et al., Evaluation of damages due to alkali-silica reaction with nonlinear acoustics techniques, POMA 7, 045003 (2009)

Appendix B

Acoustics 2012 Proceedings II

Probing materials damage at various depths by use of Time Reversal Elastic Nonlinearity Diagnostic: Application to concrete

ACOUSTICS 2012

Probing materials damage at various depths by use of Time Reversal Elastic Nonlinearity Diagnostic: Application to concrete

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Time Reversal Elastic Nonlinearity Diagnostic (TREND) is based on the use of time reversal to focus energy at a prescribed location. This focused elastic wave energy is then analyzed for nonlinear frequency content. By varying the frequency content of the focused waveforms, the technique can be used to probe different depths relative to the surface, i.e., the TREND will probe the surface and penetrate to a depth defined by the wavelength of the focused waves. We show the validity of this concept by comparing the results obtained from nonlinear resonant ultrasound spectroscopy and the present results in the presence of homogeneously diffused damage in concrete.

1 Introduction

The principle of time reversal acoustics is based on a simple principle. In any medium, send a pulse from a source and that pulse propagates into the medium. The wave is eventually reflected many times at boundaries and other scatterers, during which time the resulting signal is recorded at a given location by a receiver. If the recorded signal is time reversed and sent back from the receiver, the wave will play this propagation history backward (as a movie played backward), then the energy will focus at the precise emitter location at a given time (namely the focal time). Thanks to the reciprocity principle, the same scenario can be reached even if the time reversed signal is sent back from the initial source. In this case the focus will occur at the receiver location. This is true with a single emitter but the multiplication of emitters allows reaching an higher amplitude at the focal time.

This physical principle has been under study for many years, and has been largely developed by M. Fink [1] with most of the application in liquids or tissues for the medical field. The application of this principle to solids was developed at LANL with the idea to use the high energy focus to extract some nonlinear properties of solids. It has been successfully applied to locate and image cracks in a metal component [2], to evaluate the quality of diffusion bonds [3], and many other advances made in the field. However, the idea of using various frequencies to probe the material at different depths (with respect to the wavelength) has never been studied. This is the purpose of the present study.

To validate this idea, the comparison of the TREND results is achieved with respect to those obtained by a reference Nonlinear Resonant Ultrasound Spectroscopy (NRUS) measurement for the same samples [4]. Refer to this paper for details about samples and NRUS results. The concrete samples are chosen as they exhibit the largest nonlinear behavior (from [4]).

2 Experiments

The experimental protocol given Fig. 1 is based on reciprocal time reversal. The sample is placed onto a reverberant cavity which is a simple aluminum block with 8 piezoelectric discs (emitters) bonded to the surface at various locations. This cavity allows multiple reflections to occur, delaying the information available over time, and so, increasing the efficiency of the time reversal process. It is important to notice that we use a standard ultrasonic coupling agent; this point will be underlined at the end of the report. The laser records the signal at the top of the sample. An 8 channel 14-bit generator/digitizer system associated with 8 channels power amplifier is used. A PC controls the TR experiments and allows to move the sample with a synchronized motion controller.

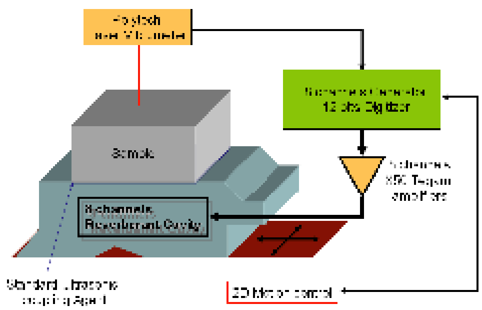

Figure 1: Experimental protocol

The signal processing is given in Fig. 2. Five frequencies (f=50, 100, 200, 300 and 400 kHz) corresponding to various wavelengths are selected. Note that the wavelength varies as a function of speed of sound v as $\lambda = v/f$. With the support of Fig. 2, the following steps occur:

1. A chrip signal (sinusoid with frequency varying in a given range) is sent to one emitter.
2. The signal is recorded by the laser, cross-correlated with the initial chirp signal (this operation allows getting the impulse response of the sample in the selected frequency range) and recorded by the system.
3. The same chirp is emitted from another emitter and stored too. (This process is applied for each channel).
4. When the 8 impulse responses are recorded, all of them are time reversed and sent back from their initial emitter at the same time.
5. The laser records the resulting focused signal.

In order to measure the nonlinearity, we need to measure the effect of amplitude. Thus, step 4 is repeated for 16 various amplitudes for each channel, providing 16 focused signals with different amplitudes. This protocol is repeated at 2 other locations on the sample.

The nonlinearity is extracted by the Scaling Subtraction Method (SSM). This method introduced by Scalerandi [Scalerandi, 2008] allows evaluating the nonlinearity from propagating waves. This principle can be explained by: send a signal s1 with an A1 amplitude and record it (r1) after propagation. Send a signal s2 with an amplitude A2 and record it (r2) after propagation. In a perfect linear medium, the scaled substracted signal (SSM signal) ssm = r2 - A2/A1*r1 will be zero. But, in a nonlinear medium, as the amplitude affects the propagation, the ssm signal will not be zero. One can measure the maximal amplitude or the energy of the SSM signal to get information about the amount of nonlinearity.

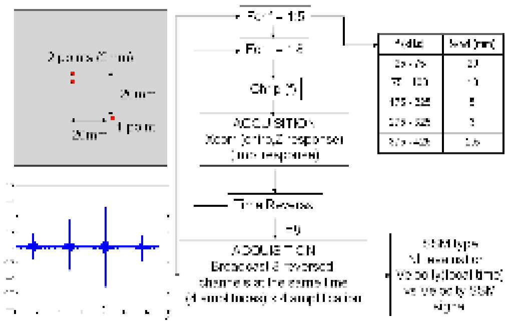

Figure 2: Data processing

The penetration depth is expected to correspond to the half pressure wave wavelength. This assumption is checked in the following section by the help of numerical simulation.

3 Numerical simulation

A 2D time reversal experiment has been modeled using Comsol to validate our hypothesis of the penetration depth that may correspond to the half pressure wave (i.e., compressional) wavelength. Figure 3 presents this simulation. To simplify the simulation, the standard Time Reversal process is modeled instead of reciprocal TR. A pulse is sent at the laser spot location, then the resulting signal is recorded by the transducers (direct signals Fig. 27). The receivers then become emitters and send back the time reversed signal they recorded, providing a focus at the laser spot location. An image of the volumetric strain inside the sample is provided in fig. 4.

This result validates our hypothesis about the penetration depth. The evolution of strain at the surface is due to surface waves, but at the focal time in the focal zone, pressure waves dominate. The pear shape observed is coherent with the results available in the literature [5].

This validation made, full 3D simulations should be performed to quantitatively link the measured velocity at the laser spot to the true volumetric strain (as for simulations in the NRUS section) for various frequencies.

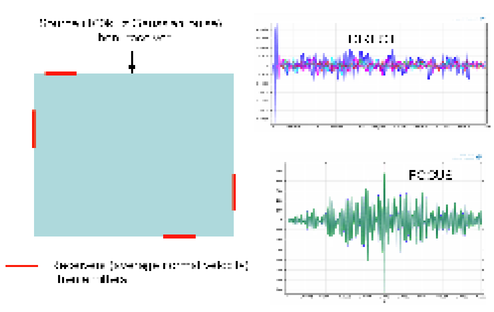

Figure 3: Numerical simulation configuration

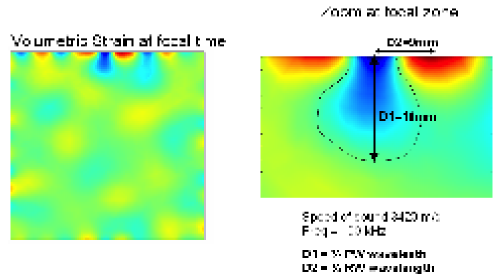

Figure 4: Volumetric strain at focal time. PW : pressure waves, RW : Raleigh waves

4 Results and discussions

The results for concrete samples are provided in Figs. 5 - 9. Note that for a comparison purposes, the procedure is also applied to the linear Plexiglas sample. The blue, green and red dots are respectively the 1st, 2nd and 3rd measurement points (refer to Fig. 2). The nonlinear indicator is evaluated as the ratio of the SSM signal energy by the fundamental energy (energy recorded at the focus). The 3 points for each penetration depth level correspond to the 3 measurements points. The 50kHz results are shown but as the sample size is about 5x10x10cm3, this frequency produces wavelengths comparable to the thickness of the samples, so these frequencies may not be very representative (i.e., possibly corrupted due to edge effects). The same observation can be made for 400kHz frequency because the wavelength corresponds to a small scale with regards to the concrete spatial variability. The compilation of the results (Fig. 10) presents the average of the measured nonlinearity at the 3 points for each wavelength.

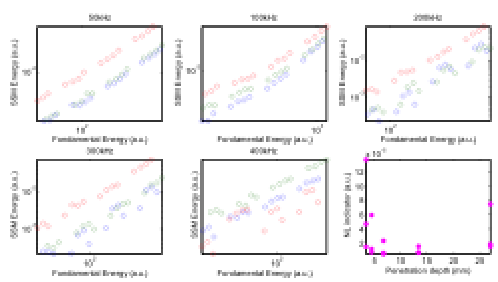

Figure 5: TREND result for the Plexiglas sample

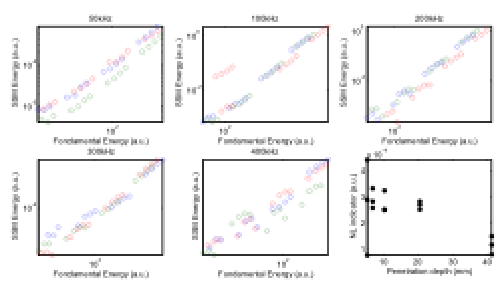

Figure 6: TREND result for the OC20 sample

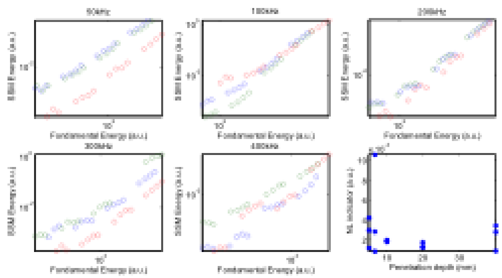

Figure 7: TREND result for the OC120 sample

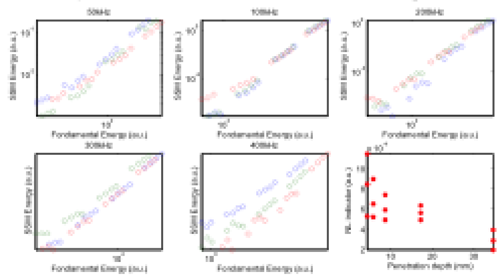

Figure 8: TREND result for the OC250 sample

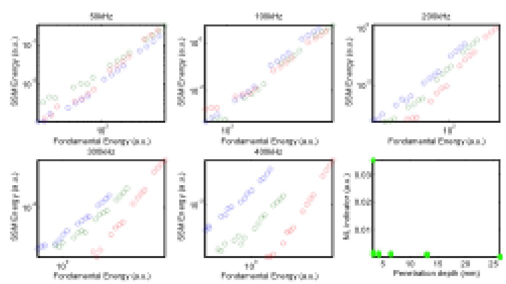

Figure 9: TREND result for the OC400 sample

We take part to provide the "raw" results even if they may be smoothed by rejecting some points that seems to be non-physical or by additional data processing. As is, these results from Figs. 5-9 and Figs. 10-11 highlight:

1. The reference Plexiglas sample, as expected, exhibits nonlinearity an order magnitude lower than concrete samples (as for NRUS).
2. For each wavelength, the nonlinearity of OC400 is 10 times the one of OC20 (as for NRUS).
3. For each wavelength, the nonlinearity of OC20 is comparable to the one of OC120 (as for NRUS).
4. The average nonlinearity evolution for each sample (other 3 points and each wavelength) matches NRUS results very well (Fig. 11).

The data scatter increases with increasing frequency and at low frequency, which may be due to:

1. The variability of concrete at low penetration depths (few mm). That should be solved by applying this procedure to more points at the surface.
2. The 8 piezoelectric discs used are the same ones, with the same frequency characteristics. So by using an adapted cavity for a given frequency range should be valuable.
3. At low frequency, the wavelength is of the size of our samples, so some particular undesired effects may appear such as resonance modes.

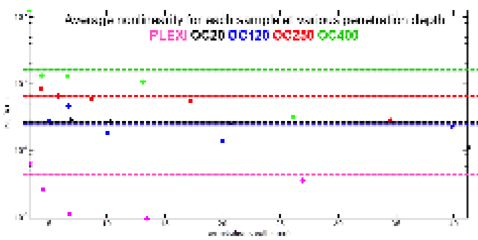

Figure 10: Compilation of TREND results for Plexiglas (pink), OC20 (black), OC120 (blue), OC250 (red) and OC400 (green) samples. Dotted lines are the average nonlinearity for each sample.

Globally, the nonlinearity seems to decrease with the penetration depth. This point is under study but no conclusion can be drawn at this point. By looking at the best frequency range (100-300 kHz), the one for which the piezoelectric discs are the more efficient and the wavelength is not too low with regard to concrete variability, the nonlinearity is more or less constant. This question will be answered by numerical simulation that may allow understanding of the strain evolution as a function of the penetration depth.

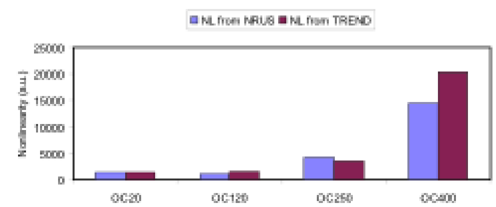

Figure 11: Average Nonlinearity evolution over each wavelength (normalized / OC20's NRUS nonlinearity)

5 Conclusion

We show in this paper the feasibility of using TREND at various frequencies to probe concrete nonlinearity at various depths. This represents an advance in the field. Even without changing the frequency, this is the first time that time reversal is employed to probe nonlinearity in the presence of diffuse damage. The correlation with NRUS results (refer to [4]) was not expected with such a confidence. Thus, even if further studies are needed to become quantitative, using TREND to evaluate concrete integrity is very promising.

References

[1] Fink, M, Time reversal of ultrasonic fields. I. Basic principles, IEEE Trans Ultrason Ferroelectr Freq Control. 39(5):555-66 (1992)

[2] Ulrich, TJ, Johnson, P. A., and Guyer, R. A., Interaction Dynamics of Elastic Waves with a Complex Nonlinear Scatterer through the Use of a Time

Reversal Mirror, Physical Review Letters 98, 104301 (2007)

[3] Ulrich, TJ, et al., The time reversed elastic nonlinearity diagnostic applied to evaluation of diffusion bonds, Applied Physics Letters, 93, 151914 (2008)

[4] Payan. C, TJ Ulrich, PY Le Bas, M. Guimaraes, Quantitative linear and nonlinear resonant inspection techniques for characterizing thermal damage in concrete, Acoustics 2012 Proceedings, Nantes April 23-28th 2012 (France).

[5] Janssen E., Van Den Abeele K., Dual energy time reversed elastic wave propagation and nonlinear signal processing for localisation and depth-profiling of near-surface defects: A simulation study, Ultrasonics 51(8), 1036-1043 (2011)