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Concrete cover characterisation using dynamic acousto-elastic testing and Rayleigh waves

Quang Anh Vu [a,*], Vincent Garnier [a], Jean François Chaix [a], Cédric Payan [a], Martin Lott [a], Jesus N. Eiras [b]

[a] Aix-Marseille Université, LMA UPR 7051, IUT Aix-en-Provence, 413 Av. Gaston Berger, 13100 Aix-en-Provence, France
[b] Instituto de Ciencia y Tecnología del Hormigón (ICITECH), Universitat Politècnica de València, Camino de Vera s/n, 46022 València, Spain

HIGHLIGHTS

- Dynamic acousto-elastic testing by using Rayleigh waves as probe wave and the first bending mode excitation as pump wave.
- Nonlinear dynamic acousto-elastic behaviour of concrete.
- High relative variation of nonlinear parameters for assessment of thermally damage concrete and carbonated concrete.
- The method opens up new possibilities for in situ measurement.

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ABSTRACT

This paper presents the application of surface Rayleigh waves in nonlinear dynamic acousto-elastic testing for the nondestructive evaluation of the concrete cover. Numerous physical phenomena, such as conditioning and slow dynamics, characterising the dynamic non-classical nonlinear elastic behaviour of many types of micro-heterogeneous solids, were observed in concrete. Rayleigh waves were used as probing waves to evaluate the effect of local property changes in a concrete cover. The proposed method was validated for two typical problems of concrete durability, in a case of thermal damage – distributed micro-damage – and in a case of carbonation – surface problem with determination of the carbonation depth. In both cases, the results showed that the relative variation as a function of material changes of the nonlinear parameters was much higher than that of the ultrasonic pulse velocity.

1. Introduction

This research falls within the civil engineering context of nondestructive evaluation (NDE) by ultrasound of concrete [1], and particularly of concrete cover. The external 3–5 cm concrete structure layer is most affected by various environmental factors. This layer acts as a passive film that protects the reinforcing bars from environmental impacts. Most concrete structures are large and it is difficult to conduct measurements on these structures using transmitted waves. The use of Rayleigh waves requiring only one-sided access to a structure shows potential for monitoring the integrity of concrete cover. Rayleigh waves are mechanical waves that propagate along the free surface of a solid, and transfer most of their energy to the near-surface region [2]. The effective depth of penetration of a Rayleigh surface wave is approximately one wavelength. The Rayleigh wave velocity is approximately 90–92% of the shear wave velocity. In literature, variations in Rayleigh wave velocity and attenuation have been widely studied in NDE for cement-based material characterisation [3–5]. Recently, classical nonlinear measurements based on the second harmonic generation of Rayleigh waves have been developed to evaluate near-surface nonlinearities for different concrete structures [6,7]. These recent developments allow for evaluations of either linear acoustic parameters or classical nonlinear parameters.

Concrete is a strongly heterogeneous material. The elastic behaviour of concrete-like materials is known as being nonlinear strain-dependent [8–12]. In the nonlinear elastic theory of Murnaghan [8], where a strain above 10^{-4} is applied to a material by quasi-static solicitation, acousto-elastic measurements showed that the elastic modulus variation is a linear function of the strain amplitude. This linear variation allows for the experimental extraction of the third order elastic constants l, m and n [13–15]. At lower strain amplitude, 10^{-7}–10^{-5}, under dynamic solicitation, the mate-

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* Corresponding author.
E-mail address: quanganhdhgt@gmail.com (Q.A. Vu).

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rial exhibits hysteresis during loading cycles. This behaviour has been studied in some types of rock [19–23]. Once the material is stressed dynamically, its elastic properties decrease and it reaches a nonequilibrium dynamic state [9]. The material now is considered as being conditioned. Thus, the nonlinear evolution of the modulus is described as a function that includes high order strain terms, strain amplitude and strain rate [10].

$$M(\varepsilon, \dot{\varepsilon}) = M_0\{1 + \beta\varepsilon + \delta\varepsilon^2 + \ldots + \alpha[\Delta\varepsilon, \varepsilon \cdot sign(\dot{\varepsilon})]\} \tag{1}$$

In Eq. (1), M_0 is the linear elastic modulus; $\Delta\varepsilon$ is the local strain amplitude variation, $\dot{\varepsilon} = d\varepsilon/dt$ is the strain rate, $sign(\varepsilon) = 1$ if $\dot{\varepsilon} > 0$ and $sign(\varepsilon) = -1$ if $\dot{\varepsilon} < 0$. The parameters β and δ are the classical quadratic and cubic nonlinear parameters of the classical nonlinear theory, respectively, whereas α is a nonclassical nonlinear parameter that represents material hysteresis. Note that Eq. (1) is a phenomenological description of fast dynamics, especially for NDE applications. It does not include slow dynamics that correspond to the time-dependent recovery of the elastic properties after a disturbance. In this study, the slow dynamics were also observed experimentally, but were not analysed.

Many NDE nonlinear acoustic techniques, such as nonlinear wave modulation spectroscopy (NWMS) [24] and nonlinear resonant ultrasound spectroscopy (NRUS) [25], are based on the model in Eq. (1). According to the general trend observe from these studies, nonlinear acoustic parameters showed a much higher sensitivity to material changes than linear measurement parameters, particularly to damage-associated changes. In the literature on cement-based materials (mortar and concrete), nonlinear acoustic techniques showed their efficiency in evaluating different ageing problems due to mechanical or environmental impacts, for example corrosion of the reinforcing bars [26], alkali-silica reaction [27,28], static mechanical loading [29,30], thermal damage [31–34], carbonation [7,35,36].

Among nonlinear techniques, dynamic acousto-elastic testing (DAET) is noticed as providing a more complete insight into the acoustic nonlinearity exhibited by micro-inhomogeneous media like granular and cracked materials. This recently developed method [16–22] allows us to analyse the elastic behaviour of the material during entire loading cycles. Thus, both the classical and nonclassical parameters can be extracted. Based on the "pump-probe" principle [15], we chose to use a Rayleigh wave as probe wave in our measurement for its ability to conduct local inspection. A technique based on a similar principle to study indirect and semi-indirect transmission configurations was presented by Bui et al. [37]. In this reference study, only one high frequency pulse was used as probe wave, whereas the pump wave was generated by a mechanical impact. The nonlinearity information extracted was the sum of time shifts analysed by using a window sliding over the probe signal.

Our proposed methodology was applied to thermal damage and carbonation of concrete. Thermal damage is in the form of distributed micro-cracking and it was showed that the nonlinear parameters were highly sensitive to the evolution of this damage [31–34]. Carbonation depth evaluation represents a gradual surface problem, which is still a challenge for nondestructive techniques.

In this paper we analyse the nonlinear parameters measured in a DAET experiment using Rayleigh waves, applying the technique to two typical concrete durability problems. In the first section the mechanisms of thermal damage and carbonation are described, and information on the concrete samples is given. Next, all the DAET experimental conditions are explained. The results are discussed and then compared with results reported in the literature. Finally, we provide conclusions on nonlinear Rayleigh wave ultrasonic measurement, and propose some prospects.

2. Materials and methods

2.1. Materials

In this part, the description of microstructural changes occurring in concrete caused by thermal damage and carbonation is presented. Each case study consisted of a series of concrete samples. Before being tested for nonlinear DAET measurement, all the samples were characterised based from velocity measurements. The elastic modulus and Poisson's ratio were thus estimated according to their reciprocal relationship with the pressure velocity and shear wave velocity. The density of each sample was quantified by the ratio between mass and volume. All these values are presented in detail in the next section.

Bulk wave measurement was performed by transmission, while Rayleigh wave measurement was performed using two contact piezoelectric transducers mounted on two wedges to generate an incident wave with a specific angle. The measurements of both the pressure wave velocity and Rayleigh wave velocity were made using two Panametrics-NDT ultrasonic transducers (model V101, central frequency 250 kHz). Two Panametrics-NDT transducers (model V151, central frequency 250 kHz) were used for shear wave velocity measurements.

As for the generation of the Rayleigh waves, the wedges were made of Polytetrafluoroethylene (PTFE), in which the pressure wave velocity is 1250 m/s. The wedge inclination angle had been set at 45° – which is generally bigger than the second critical angle of all the samples – to attenuate the bulk waves as much as possible during Rayleigh wave generation. It was observed that the bandwidth of a Rayleigh wave in a concrete sample was limited at about 170 kHz. Beyond this limit, the signal-to-noise ratio of the received signal was very low. Thus, we chose to work with 100 kHz waves for different reasons. The source signal was set as an impulse-type signal – one cycle burst at 100 kHz with 150 V of input voltage. The frequency spectrum of the received signal is centred at 90 kHz. The first reason for the choice of frequency and high voltage was to achieve a good signal-to-noise ratio for the Rayleigh waves. The second reason was that Rayleigh waves were considered as propagating within approximately 22 mm of the surface layer (corresponding to one wavelength). Therefore, the carbonation depth in all the carbonated concrete samples presented below could be covered by the penetration depth of the Rayleigh wave.

2.1.1. Thermal damage

Thermal damage is referred to for concrete structures (e.g., domestic residences, tunnels) in the context of fire attacks or for radioactive waste packages that continue to radiate heat. At 105 °C, free water and physically adsorbed water evaporate [17]. The porous structure of concrete is slightly modified. Upon heating to 400 °C, the total porosity increases gradually. The network of interconnected pores resulting from micro-cracking becomes coarser. At 450–500 °C, chemical reactions begin, which leads to changes in the microstructure. Above these temperatures, concrete becomes severely damaged.

In this work, experimental tests were conducted on four prismatic concrete samples ($90 \times 90 \times 260$ mm^3). The concrete had a water cement ratio of 0.44 and contained fine aggregates of maximum size $d_{max} = 8$ mm. Samples were cured for more than 28 days and were subjected to different heat treatments – T1 was kept intact and T2, T3 and T4 were heated to 180 °C, 250 °C and 400 °C – involving 24 h heating in a furnace and 24 h cooling. Sample designations and measured properties are summarised in Table 1.

The main consequence of a heat treatment (heating and cooling) is the generation of distributed cracks and a decrease in density as a function of temperature. An increase in volumetric degradation due to heat treatment is indicated by the decrease in bulk wave and Rayleigh wave velocities.

2.1.2. Carbonation

What is called carbonation is the progressive formation of calcium carbonate in concrete due to the penetration of carbon dioxide (CO_2) from air (there is a small amount of CO_2 in the pores) that reacts with calcium hydroxide $Ca(OH)_2$ in the cement paste. The chemical reactions can be described as [35]:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

Table 1
Thermally damaged samples data.

Designation	T1	T2	T3	T4
Heat treatment	Intact	180 °C	250 °C	400 °C
ρ (kg/m^3)	2240	2131	2128	2119
$V_{pressure}$ (m/s)	4628	3927	3718	3008
V_{shear} (m/s)	2578	2307	2236	1838
$V_{Rayleigh}$ (m/s)	2354	2106	2042	1678
E (GPa)	38.5	28.0	25.9	17.2
ν	0.275	0.236	0.217	0.202