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Acoustoelastic effect in concrete material under uni-axial compressive loading

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This study deals with the general matter of non-destructive evaluation of pre-stressed structures in civil engineering. Usually such structures are composed of concrete and are steel reinforced. Proposed idea is the evaluation of mechanical stress state of a concrete body (instead of steel cables) via ultrasonic non-destructive evaluation (NDE), by using the link between ultrasonic velocities and mechanical stresses provided by the acoustoelasticity theory. Velocities of the ultrasonic waves (longitudinal and transversal with different polarizations) are observed during propagation through a concrete body submitted to uni-axial loading (compressive testing). Obvious variations in velocity are found depending on the mechanical stress state (e.g. $\Delta c = 92$ m/s at $\sigma = 16$ MPa for longitudinal waves). Thus acoustoelastic behavior of concrete is demonstrated. Further analyses provide acoustoelastic coefficients of concrete about ten times higher than the common ones of steel. The feasibility of stress evaluation using ultrasounds in concrete structures is proved under laboratory conditions.

1. Introduction

Regarding the durability of civil engineering structures, non-destructive characterization is a high-performance method to obtain in situ data and hence improve the evaluation of the potential remaining service life of real structures [1]. Such structures are often composed of concrete matrix pre-stressed using steel bars or cables. This technology improves the mechanical response of the structure by limiting concrete loading to compression. In this way, steel cables are submitted to stresses that vary if the structure is externally loaded. Non-destructive evaluation (NDE) of the mechanical state of the structure results in stresses evaluation in the concrete or in the cables. The complexity of concrete material as compared to steel has resulted in several studies on the analysis of the steel cables, these studies aiming to detect cable defects [2–4]. Each cable is composed of several major strands and each major strand is composed of several smaller strands twisted together. The path of the cable can be complex, and access to the cables may be impossible. This configuration is problematic for the different non-destructive techniques that could be used; this is why no accurate solution currently exists to evaluate stresses in cables.

The major challenge proposed in this article is evaluating compressive stresses in the concrete matrix instead of cables. Among the various non-destructive techniques, the ultrasonic

waves can be easily linked to the mechanical state of the inspected part. Concrete is a heterogeneous material and exhibits a complex elastic behavior related to the presence of microcracks and porosity even if damage has not occurred. That results in a nonlinear and viscoelastic behavior [5,6]. In this case, ultrasonic wave propagation is dependent on structure stresses and acoustoelasticity [7] establishes the mathematical relationships between the ultrasonic velocities and strains or stresses in the studied material. The main objective of this study is to evaluate and display the acoustoelastic effect in concrete when elastically loaded. The Section 2 of the manuscript makes a survey of the acoustoelasticity studies encountered in the literature for different materials, and describes general theory of acoustoelasticity in homogeneous media. This leads to the definition of acoustoelastic coefficients. Section 3 introduces the particular experimental set-up developed to obtain ultrasonic data during uni-axial compressive loading. The different samples are described together with their composition and mechanical parameters. Section 4 details the various velocities measured as a function of compression stress level. The resulting acoustoelastic coefficients are compared with the ones obtained in literature for other materials.

2. Ultrasonic wave behavior in mechanically stressed media

2.1. Review of ultrasonic stress evaluations

Acoustoelasticity theory is based on the nonlinear behavior laws derived by Murnaghan [8]. When a material exhibits a

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nonlinear elastic behavior, it is possible to determine acoustoelastic coefficients that express the linear functions between ultrasonic velocities and stress state of first order. Based on the study of ultrasonic velocities variations and on known acoustoelastic coefficients, the static stress level in the material can be evaluated. In the first validation study [7], theoretical works are compared to experimental data obtained for polystyrene and glass. The fact that the experiments support the theoretical data proves that the theories are able to describe the velocity response to stress in the tested materials.

These results are highly relevant to the non-destructive evaluation of stressed structures, and many studies have been conducted in this regard. Steel materials are the most frequently studied materials, e.g. railroad tracks [9] or bolts [10]. Welded structures are another example, in industry, where acoustoelasticity may be an easy solution for the evaluation of residual stresses [11]. Aluminium alloys have also been studied and have been found to be a good candidate for the use of nonlinear behavior. Change in velocity strongly supports material stress state [12,13]. Rasolofosaon et al. [14] compared nonlinear acoustic and acoustoelastic methods. He evaluated Murnaghan's coefficients for several rock specimens, and he noted that these specimens exhibit highly sensitive behavior compared to that of polycrystalline materials. Few studies link changes in ultrasonic velocities to applied static compressive loading [15–17]. These studies are not limited to the elastic domain. They also compare change in velocity to change in stress when materials sustain damage. Some studies link increased microcracks in concrete to a damaging phenomenon. They aim to detect the damage threshold of the material. These studies do not focus on initial variation in velocity.

The present study focuses on the elastic nonlinear behavior of concrete. This material is heterogeneous but it can be considered as homogeneous when the wavelength is large compared to heterogeneity size and isotropic because aggregates are randomly distributed.

In this way, the following results will describe an average acoustoelastic behavior.

2.2. Acoustoelasticity theory

When motion equations are included in nonlinear elastic laws, ultrasonic velocities and strains are found to be dependent on one another. Therefore, change in mechanical stress results in ultrasonic velocities variation.

Based on Murnaghan's works concerning nonlinear elasticity for isotropic media [8], Hughes and Kelly [7] were first able to obtain analytic expressions between stress and velocities for isotropic media under hydrostatic pressure. They concluded that one possible way to evaluate Murnaghan's constants (ℓ, m, n) was to measure the time of flight of elastic waves in a given medium. For isotropic media submitted to uni-axial loading in direction 1 (2 and 3 are the other two perpendicular directions), the velocities of elastic waves are derived as follows [7,9]:

$$\begin{cases} \rho_0 c_{11}^2 = \lambda + 2\mu + \frac{\sigma_{11}}{3K} \left[2\ell + \lambda + \frac{\lambda + \mu}{\mu} (4m + 4\lambda + 10\mu) \right] \\ \rho_0 c_{12}^2 = \rho_0 c_{13}^2 = \mu + \frac{\sigma_{11}}{3K} \left[m + \frac{\lambda n}{4\mu} + 4\lambda + 4\mu \right] \\ \rho_0 c_{22}^2 = \lambda + 2\mu + \frac{\sigma_{11}}{3K} \left[2\ell - \frac{2\lambda}{\mu} (m + \lambda + 2\mu) \right] \\ \rho_0 c_{21}^2 = \mu + \frac{\sigma_{11}}{3K} \left[m + \frac{\lambda n}{4\mu} + \lambda + 2\mu \right] \\ \rho_0 c_{23}^2 = \mu + \frac{\sigma_{11}}{3K} \left[m - \frac{\lambda + \mu}{2\mu} n - 2\lambda \right] \end{cases} \quad (1)$$

where c_{ij} equals the velocity of the wave propagating in direction i and polarized in direction j , σ_{11} is the normal stress in direction 1, (λ, μ) are the first order coefficients known as Lamé's coefficients, (ℓ, m, n) are the second order coefficients, known as the Murnaghan's coefficients and $K = \lambda + \frac{2}{3}\mu$ is the compressibility modulus.

When performing linearization at the first order, this system becomes

$$c_{ij}^\sigma = c_{ij}^0 (1 + A_{ij} \sigma_{11}) \quad (2)$$

where c_{ij}^σ is the velocity of wave propagating in direction i and polarized in direction j in a medium under uni-axial stress σ_{11} in direction 1, c_{ij}^0 is the same wave velocity in the stress free medium and A_{ij} are the acoustoelastic constants which depend on Lamé's coefficients and Murnaghan's coefficients.

The initial velocities c_{ij}^0 obtained in a stress free medium can be calculated using

$$c_{ij}^0 = \begin{cases} \sqrt{\frac{\lambda + 2\mu}{\rho_0}} & \text{for } i = j \\ \sqrt{\frac{\mu}{\rho_0}} & \text{for } i \neq j \end{cases} \quad (3)$$

Exadaktylos et al. [5] validated a nonlinear elastic model to describe rock materials mechanical behavior under tensile loading. He mentioned that this model may possibly be extended to concrete. Shkolnik [6] studied the elasticity of concrete and obtained experimental nonlinear behavior (tested up to 30% of the compressive load). He found strong nonlinear elastic behavior in this situation.

The nonlinear behavior of concrete is supported by literature and the acoustoelasticity theory provided by Hughes and Kelly [7] may be used for concrete materials when considered as homogeneous isotropic medium.

3. Experimental details

3.1. Presentation of material and samples

Concrete is composed of two solid phases, these phases being the cement matrix (about 30% of the volume) and rock inclusions of various sizes (sand and aggregates, about 70% of the volume). The concrete is elaborated using a mix of cement powder with sand, aggregates and water. The water to cement ratio (generally between 0.3 and 0.6) is an important factor in the formulation of concrete. The mechanical parameters of hardened concrete depend on the cement powder composition, on the nature of rock inclusions, on the water to cement ratio and also on the hardening kinetic. The resulting concrete porosity, confined to the cement matrix, then ranges between 8% and 25%, and volume ranges from 1 Å to 1/10 μm.

Concrete is classically described in literature in terms of nonlinear elasticity [5,6]. The nonlinear behavior of concrete is attributed to microdefects that naturally exist in the cement matrix and in the rock inclusions. These microdefects can be either pores or microcracks.

The studied samples were moulded by using a regular concrete which contains 20 mm maximal size aggregates. Its quantitative analysis is given in Table 1.

The cylindrical shape of the sample provides rotational symmetric stress distribution in each 70 mm diameter section. This diameter was selected to avoid mechanical damage to the samples: the stress level is kept to less than half the measured compressive strength of the concrete (45–50 MPa) in order to avoid appearance of any damage [6]. The length of 135 mm is consistent with the machine geometry and the stress distribution

along the axis of the sample. The flat sides were sanded to ensure their parallelism.

Fig. 1 displays an example of stress–strain curve of the tested material. The nonlinear behavior is shown by the best fitting which is a second order polynomial fit.

3.2. Experimental set-up

The main purpose of this study is to design a suitable experimental set-up. The challenge is measuring ultrasonic time of flight along the three spatial axes, especially along the axis of loading, during loading. Contact transducers are placed in a cylinder bore machined through the adaptation part along axis 1 as defined in Fig. 2. Along axis 2, a pressure clamp is used to position the transducers. A spring keeps the contact pressure of

Table 1
Composition of the concrete under study.

Constituent	Content (kg m ⁻³)
Concrete	
Cement CPA CEM1 52.5	350
Sand 0/4	764
Aggregates 4/8	423
Aggregates 8/12	276
Aggregates 12/20	376
Water-to-cement ratio	0.53

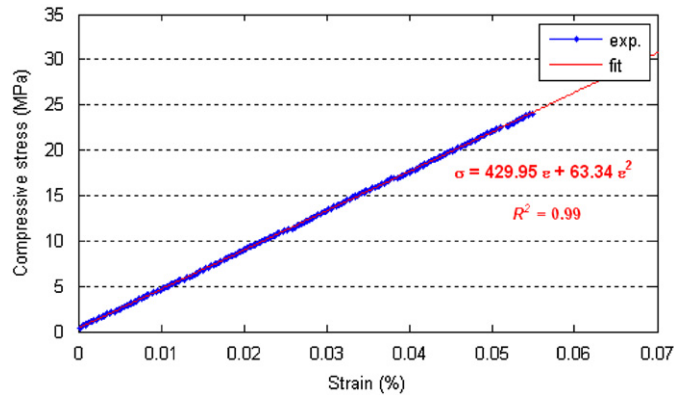


Fig. 1. Example of obtained stress–strain curve of the tested concrete.

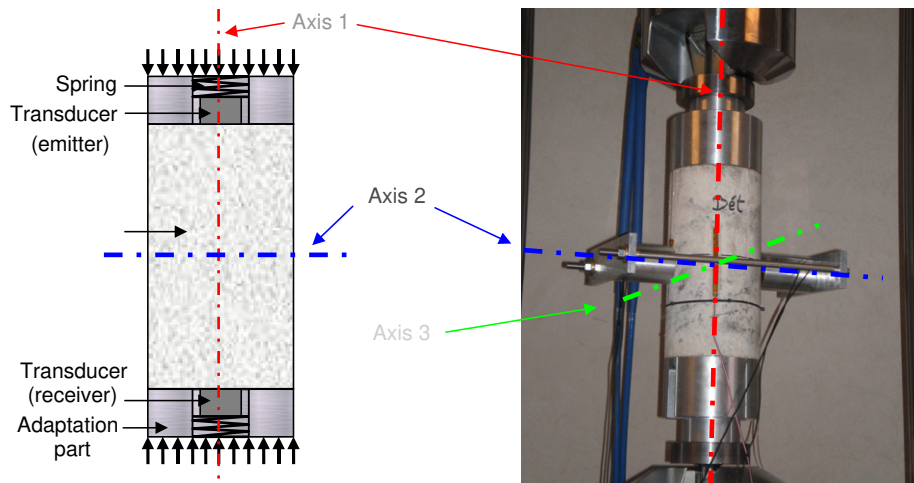


Fig. 2. Diagram and photograph of the experimental set-up.

each transducer constant during testing so that it can be assumed that the coupling layer is the same thickness during each experiment. Before each test, an initial loading increment ensures proper placement of the experimental set-up.

In this study, two pairs of panametrics ultrasonic transducers (emitter and receiver) are used: one for longitudinal waves (LW) and one for transversal waves (TW). The central frequency of each transducer is 500 kHz and each transducer has a diameter of 1". The adaptation parts are consistent with the 1" diameter of the transducers and the geometry of the sample. Nevertheless, the sample is loaded through a bearing ring and the resulting non-constant stress distribution is computed using "RDM le Mans" FEM software. For this computation concrete is assumed to be a homogeneous linear elastic material. An example of results is displayed in Fig. 3.

As shown in Fig. 3, the adaptation parts generate a significant stress gradient along axis 1. Thus all results are expressed as a function of the mean stress in direction 1 (so until 16 MPa in the following results). Along axis 2, the stress is quite constant along path of the ultrasonic wave (equal to 24 MPa in the following results).

The compressive tests are performed on a 90 kN hydraulic tension-compression computer-driven testing machine in the LMA laboratory of the CNRS de Marseille. The loading cycle includes ten 900 da N loading steps. A previous 1 kN preloading step ensures that the contacts of the experimental set-up are stabilized. The ultrasonic signals are recorded at each step as detailed in Fig. 4. After unloading, data is collected once more without any stress applied in order to verify that no damage appeared.

The acquisition system is composed of a SOFRANEL 5052 signal generator and a LECROY WaveSurfer oscilloscope as shown in Fig. 5. A Labview laboratory software allows each A-scan signal to be recorded via a computer. The acoustoelastic response for each polarization direction is tested in each propagation direction (first index). As shown in Fig. 5, five ultrasonic wave types are studied: LW1, LW2, TW1 (2 or 3) (noted TW1 in the following), TW21 and TW23.

3.3. Evaluation of variation in velocity

This study aims at evaluating the acoustoelastic response of a concrete medium, i.e., the variation in ultrasonic wave velocity when the medium is subjected to uni-axial compressive loading.

Calculation of velocity requires the measurement of wave path length and time of flight. The initial wave path length is measured using a 1/50 mm caliper (unloaded specimen). This length is corrected by the displacement measured due to the compressive system when the specimen is loaded. Moreover,

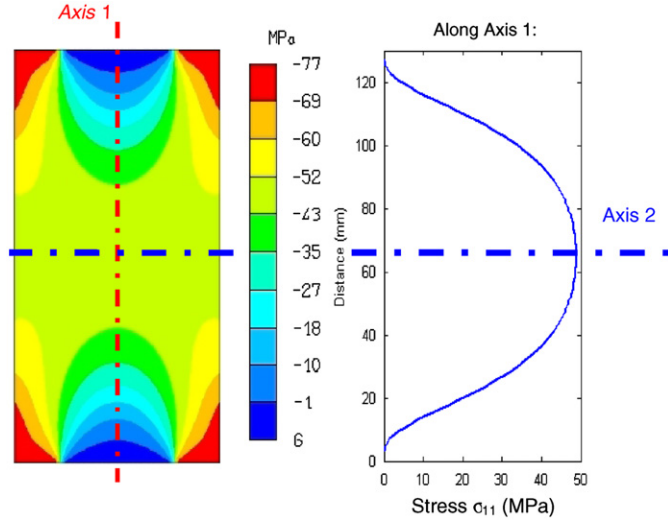


Fig. 3. Example of stress distribution calculated for the concrete sample loaded along axis 1 through a ring.

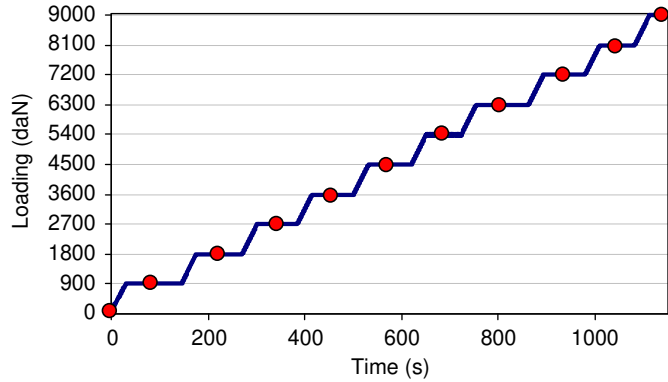


Fig. 4. Loading cycle and data collection steps.

wave propagation through concrete parts leads to multiple scattering due to prevalent material heterogeneities. As a result the second echo cannot be identified on the recorded A-scan signals as plotted in Fig. 6. Thus at each loading step, the time of flight variation Δt (Fig. 7) is computed by calculating the maximum of the crosscorrelation function between the current A-scan signal and the reference one. The reference signal is the stress free signal recorded for the considered wave mode. Note that crosscorrelation process provides information linked to the group velocity and not always for the phase one. Because of multiple scattering, the shape of the signals acquired through a concrete specimen makes the phase velocity measurement very complex. Group velocity measurement is more reliable in this case. So results are rather representative of group velocity variations. Few preliminary experiments were performed to check that group and phase velocity variations were very close. One can then assume that acoustoelasticity theory can be used with group velocity variations in this study.

On the shown signal, one can observe the effect of scattering on ultrasonic wave. The scattering depends on nature, form, size and position of the heterogeneities in the medium and also on the wavelength of ultrasonic wave. The crosscorrelation function is applied between two signals (two stress levels) obtained for exactly the same testing configuration except stress level. In the elastic domain one can suppose that the mechanical stress does not induce modifications of heterogeneities. The variation of ultrasonic velocity is then directly linked to the stress evolution.

4. Experimental results and discussion

According to relation (2), acoustoelastic computations need the value of stress free US waves celerity c_m^0 , where m represents each ultrasonic wave propagating mode (LW1, LW2, TW1, TW21 or TW23). c_m^0 corresponds to the first loading step measurement.

Because crosscorrelation computations require the c_m^0 , experimental value, no direct comparison is possible between the two experimental configurations (along axis 1 or axis 2). For this reason all results are given in terms of relative change in velocity $\Delta c_m / c_m^0$ versus the absolute value of mean axial stresses.

Figs. 8 and 9 illustrate relative variations in velocity calculated by crosscorrelation versus the mean stress level in specimen on the wave path. The mean stresses are not the same for an applied loading due to different stress repartitions for a path along axis 1 or 2 (see Fig. 3).

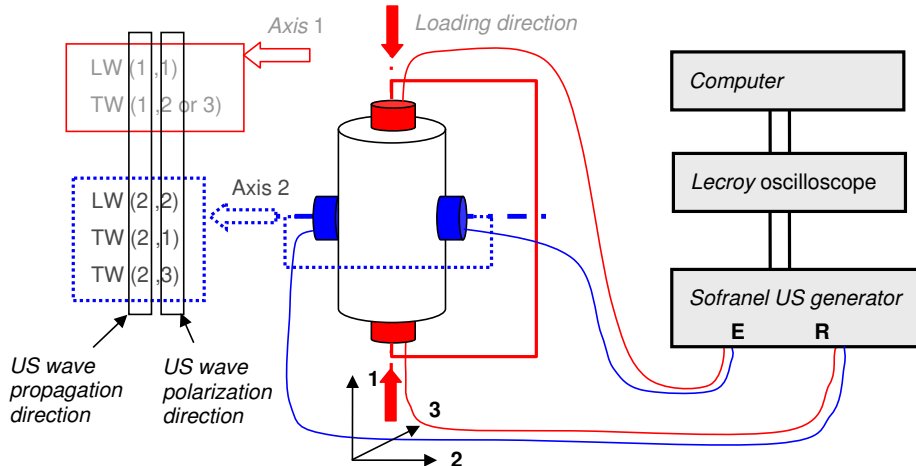


Fig. 5. Measuring process and index meaning.

Each curve indicates that the studied concrete exhibits a clearly sensitive acoustoelastic behavior. Ultrasonic wave velocities globally increase proportionally to the absolute value of mean stress.

As observed in metallic materials [9,10], an important result must be underlined: the acoustoelastic effect is greater when the ultrasonic wave polarization direction corresponds to the loading direction, here LW1 and TW21. Rasolofosaon et al. [14] found similar experimental results in rocks. As a matter of fact LW1 waves are five times as sensitive as LW2 waves and TW21 waves are three times as sensitive as TW1 or TW23 waves.

One can also note that the TW1 waves curve exhibits a no more linear behavior versus mean stress level from approximately 10 MPa. Two reasons can be set forth: particularly oriented microcracks might grow in the volume of material under investigation, or the coupling pressure might release between the transducer and the sample.

Table 2 summarizes relative variation of velocities at the mean stress level of 16 MPa. The maximum variation in velocity reaches 92 m/s for LW1. To make a comparison with a well known material, a change in velocity of 50 m/s is classically observed in steel when loading at 500 MPa. Thus concrete shows a greater sensitivity to stress than steel.

However, LW and TW velocity variations are very close for a same polarization direction. Regarding global results detailed in Table 2, the ratio between maximum and minimum velocity variations is about 5. This acoustoelastic behavior seems proper to concrete when compared to well known metallic materials [9–11]. The greatest variation still concerns the faster LW waves.

This result can be explained by the strong heterogeneity of the concrete through which wave propagation is complex [18]. Mode

conversions and deviations are numerous and depend on the scattering of the incident wave. Each wave deviation induced by heterogeneities changes the relative direction of scattered waves versus loading direction. Furthermore, internal stresses are modified by the distribution of the heterogeneities in the material. These phenomena lead to averaged results over the investigated volume.

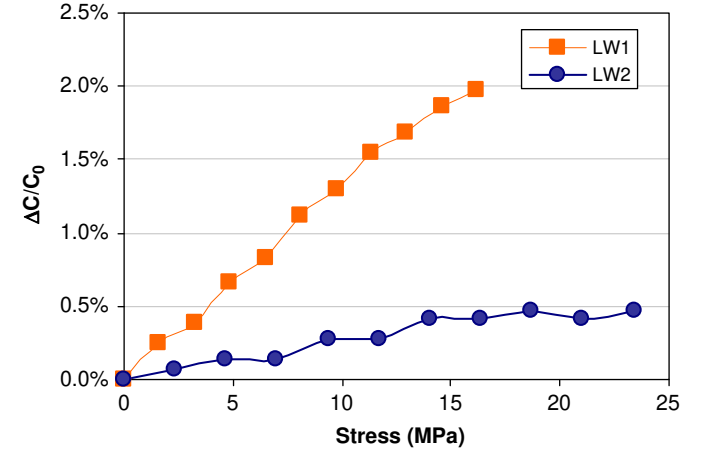


Fig. 8. Relative variations in velocity as a function of axial stress for longitudinal waves.

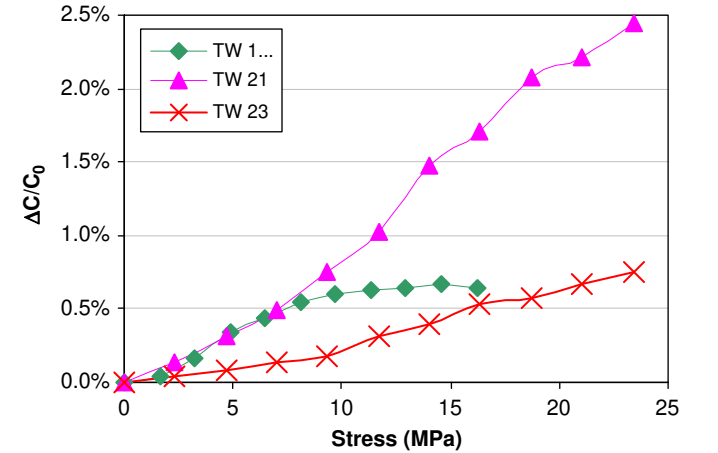


Fig. 9. Relative variations in velocity as a function of axial stress for transversal waves.

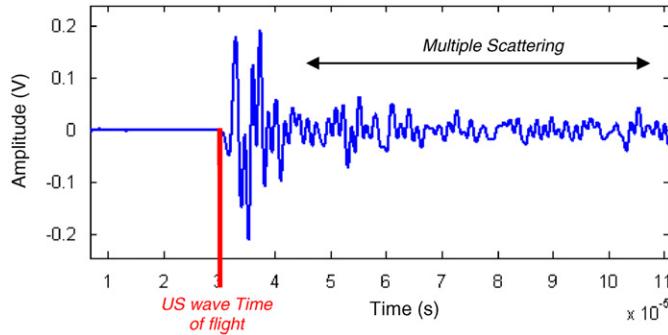


Fig. 6. Example of A-scan signal (LW) recorded in the studied concrete.

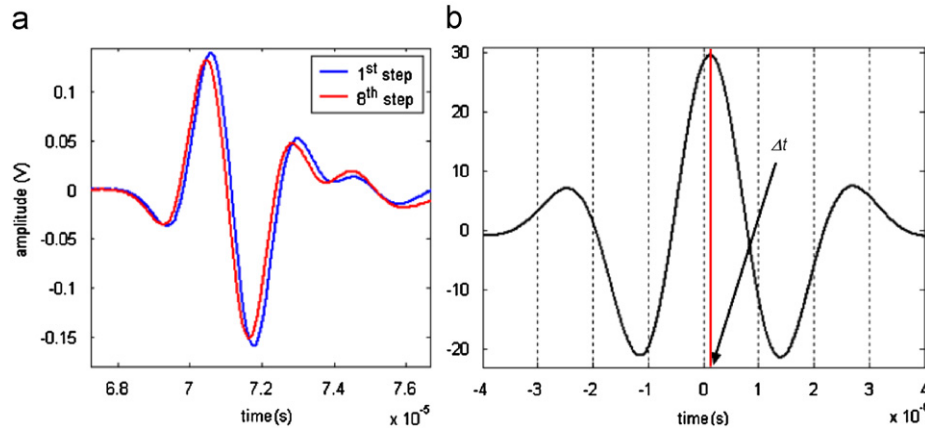


Fig. 7. Variation in time of flight between the two signals (a) and maximum of the crosscorrelation function (b).

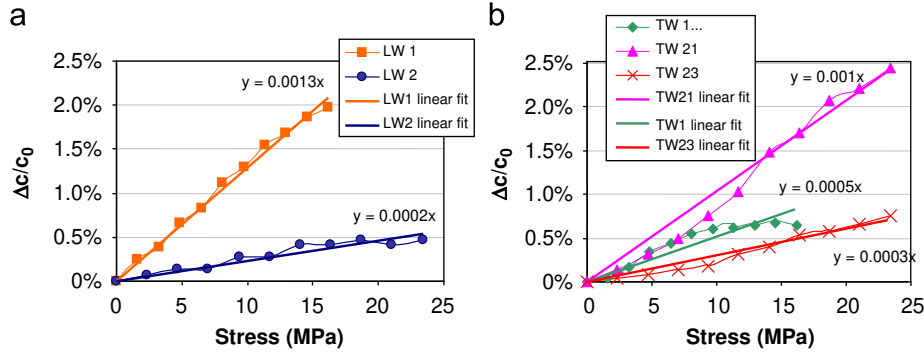


Fig. 10. Linear fit of relative velocity variations as a function of mean stress for longitudinal (a) and transversal waves (b).

Table 2
Variation in ultrasonic wave velocity at 16 MPa.

	LW 1	LW 2	TW 1	TW21	TW23
$\Delta c_m / c_m^0$ at 16 MPa (%)	1.97	0.41	0.62	1.71	0.53
Corresponding Δc_m (m/s)	92	19	20	53	17

The acoustoelastic responses have been modeled using a linear fit in order to evaluate acoustoelastic coefficients A_{ij} of Eq. (2). The results are plotted in Fig. 10. Calculated coefficients are listed in Table 3.

As noted earlier, the acoustoelastic effect in concrete is ten times higher than in standard steels [10]. The values of the R^2 coefficients prove that the experimental results support the model except for TW12 and TW13 mode. The waves polarized along the loading direction provide the best values of correlation coefficient R^2 because they exhibit the greater acoustoelastic sensitivity.

5. Conclusion

This study enhances the strong dependence between ultrasonic velocities and uni-axial static loading in concrete specimens. The most sensitive waves to stress level are the longitudinal and transversal waves polarized along the loading direction. Acoustoelastic constants have been evaluated in concrete specimens, thereby making it possible to prove the significant acoustoelastic behavior of concrete. Stress evaluation using ultrasonic measurements is then possible in concrete media. However, due to the multiple scattering of waves in concrete, it is difficult to measure ultrasonic velocities in this medium.

On another hand, stress distribution was not constant along the wave propagation path. Further investigations are planned in order to improve the experimental set-up. The main objective will be to generate a constant stress distribution in the whole inspected volume. Furthermore, the ultrasonic measurements were performed under laboratory conditions through which crosscorrelation could be processed in order to evaluate velocity variations. This calculation technique is not suitable for in situ measurements. This last obstacle is important and must be resolved to improve the non-destructive testing of concrete structures in general.

Acknowledgements

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Table 3
Estimated acoustoelastic coefficients in concrete.

	A_{11}	A_{22}	$A_{12}=A_{13}$	A_{21}	A_{23}
A_{ij}	$-1.3e^{-3}$	$-0.2e^{-3}$	$-0.5e^{-3}$	$-1e^{-3}$	$-0.3e^{-3}$
R^2 coefficient of linear fit	0.99	0.91	0.85	0.97	0.96

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