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Study of acoustoelasticity behavior of concrete material under uniaxial compression

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The general subject concerns the non destructive testing of pre-stressed structure in civil engineering structures. In this topic we interest in the feasibility of stress evaluation in concrete by ultrasonic methods. To do that, we use the acoustoelasticity theory which exploits the nonlinear behaviour of medium to establish the link between stress and ultrasonic velocity. This theory had been validated in homogeneous media and used in steel to evaluated stresses in steel bolt for example. The concrete is a heterogeneous medium where the ultrasonic velocity measurement is more difficult than in steel. The scattered waves induce uncertainty in the measured values but the nonlinear behaviour of concrete is more important than the one of steel. We show an application in high performance concrete submitted to uniaxial compression. We measured velocities of longitudinal and transversal transmitted ultrasonic waves in the direction of the stress and perpendicular to the stress at different stage of the stress test. The sensibilities of the velocities are observed and the potential to evaluate stress in concrete is shown. The prospect concern the widening of formulation tested and the in situ measurements. This study is supported by ANR-ACTENA, a French research program.

1 Introduction

General problem handled by project ACTENA concerns non destructive testing of non accessible prestressing cables in the final aim of determination of residual stress. The reasoning way that we privileged consists in considering consequences rather than causes. Thus we proposed to try to characterize residual stresses not at the cables level but at the level of the stress field transferred to accessible concrete foundations around cables.

2 Acoustoelasticity theory

Integrating elastic non linear behaviour laws into motion equations leads to a dependency of ultrasonic velocities to material strain and so to stress level to which the material is subjected.

Based on Murnaghan works [1] concerning non linear elasticity in isotropic medium, Hughes et Kelly [2] obtain for the first time the relationships linking ultrasonic velocities and strains in an isotropic medium under hydrostatic pressure. Authors conclude on the ability to Murnaghan constants (ℓ, m, n) using transmission time measurement of elastic waves.

For uniaxially loaded medium in direction 1 (2 and 3 being perpendicular), elastic waves velocities are written as a function of stress [2]:

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

where $K = \lambda + \frac{2}{3}\mu$ is the bulk modulus.

First order linearized system can then be written as follow:

$$\begin{aligned} V_{ij}^{\sigma_{11}} &= V_{ij}^0 (1 + A_{ij} \sigma_{11}) \\ \Leftrightarrow \frac{V_{ij}^{\sigma_{11}} - V_{ij}^0}{V_{ij}^0} &= \frac{\Delta V_{ij}}{V_{ij}^0} = A_{ij} \sigma_{11} \end{aligned} \quad (2)$$

where $V_{ij}^{\sigma_{11}}$ denotes the velocity of the wave propagating in i direction with a particular displacement in j direction in a medium subjected to an uniaxial stress σ_{11} in direction 1.

V_{ij}^0 is the velocity of the wave propagating in i direction with a particular displacement in j direction in the same medium without stress ($\sigma_{11} = 0$). A_{ij} are acoustoelasticity constants dependant of Lamé coefficients (λ, μ) and of Murnaghan coefficients (ℓ, m, n).

3 Concrete and ultrasounds

3.1 Composition of concrete

Concrete is a composite material constituted of two solid phases: a matrix made with cement and rock inclusions (60 to 70% of volume). Concrete elaboration deals with a binder like cement, sand, fine gravel and water. Other elements named adjuvants can complete the formulation with weak quantities. Water on cement ratio (E/C) is a data characteristic to concrete formulation generally between 0,3 and 0,6. Concrete characteristics depend on those of cement and rocks entering the composition (cf. table 1).

Material	Density (kg.m ⁻³)	Modulus of elasticity E (MPa)	Poisson coefficient ν
Rock	2 600 - 2 700	60 000 - 90 000	0,2 - 0,3
CPA cement	~ 2 100	30 000 - 40 000	0,2 - 0,3

Table 1: Mean characteristics of rock and cement.

Concrete setting involves chemical, mechanical and thermal mechanisms. A part of the air present during elaboration keeps enclosed in cement paste or at the interfaces paste/aggregate in the shape of pores. Porosity rate is generally included between 10 and 25% and pore sizes vary from angstrom to tenth of micrometer [3,4]. These initially

present pores influence the characteristics of concrete and also their variations during loading.

3.2 Models of concrete mechanical behaviour

General mechanical behaviour described in literature exhibits this material as elastic, fragile and damageable [5]. Elastic part is modelled in a linear or non linear way [6] according to needs. Thus elastic behaviour in compression seems to be non linear but no clear limit has yet been established between this domain and a domain with damage as a shape of microcracks evolution [7] in cement matrix. Variety of concrete formulations leads to a large range of materials with various mechanical properties.

3.3 Ultrasonic measurements and concrete subjected to mechanical stresses

Few works have been conducted concerning influence of stress state on ultrasonic wave propagation in concrete. Popovics [8], Berthaud [9], Wu [10] and Qasrawi [11] are main publication authors upon this subject.

Heterogeneous nature of concrete makes difficult the processing and interpretation of ultrasonic signals. Actual measurements realised on concretes under compressive stresses did not display acoustoelastic behaviour [8]. Nevertheless velocity measurements have very rarely been performed in loading direction and often for only one wave pattern: longitudinal waves [9].

The weak number of studies on acoustoelastic behaviour and the evolution of measurement methods led us to propose a complete feasibility study on measurements of longitudinal and transverse wave velocities for several compositions subjected to uniaxial compressive stresses.

4 Experimental protocol

4.1 Composition and geometry of specimens

Specimens are cylinders with various diameters from 53 to 160 mm and coefficient of elongation (L/D) close to 2 to enable realise compression testing. Variety of diameters allows adapting specimen geometry to ultrasonic transducers dimensions. Five compositions (cf. table 2) were studied (M=Mortar, M+4/10=Mortar with 4/10 aggregates, M+10/16= Mortar with 10/16 aggregates, HPC=High Performance Concrete, OC=Ordinary Concrete) to be able to analyse the influence of aggregate distribution.

Moreover a rock (parallelepiped) specimen was also studied. It was obtained from the rock constituting sand and aggregates.

Compression strengths (R_c) and Young moduli (E) were measured through destructive testing (by the "Centre d'Etude et Technique du ministère de l'Équipement", cf. table 3).

Component	M	M+4/10	M+10/16	HPC	OC
Cement CPA 52.5	660	550	475	415	350
Water	300	250	215	187	185
Adjuvant	6,6	5,5	4,8	4,1	764
Sand 0/4	1375	1150	985	865	-
Aggregates 4/10	-	470	-	355	-
Aggregates 10/16	-	-	810	710	-
Aggregates 4/8	-	-	-	-	423
Aggregates 8/12	-	-	-	-	276
Aggregates 12/20	-	-	-	-	376

Table 2: Compositions of tested concretes ($kg.m^{-3}$).

Parameter	M	M+4/10	M+10/16	HPC	OC	Rock
R_c (MPa)	87,7	82,9	79	76,6	50	205
E (GPa)	32	35	39,5	42,8	30	80,4

Table 3: Compressive strength and Young modulus.

Some specimens were equipped with strain gages with length 50 or 100 mm according to specimen dimensions and size of the largest aggregates.

4.2 Compression loading setup

Used loading setup enables positioning of ultrasonic transducers in the axis and perpendicularly to loading. Disposition of transducers imposes a circular area with null stress at the centre of support face. This induces a non homogeneous repartition of compressive stress on the specimen axis particularly for smallest specimens (cf. figure 1).

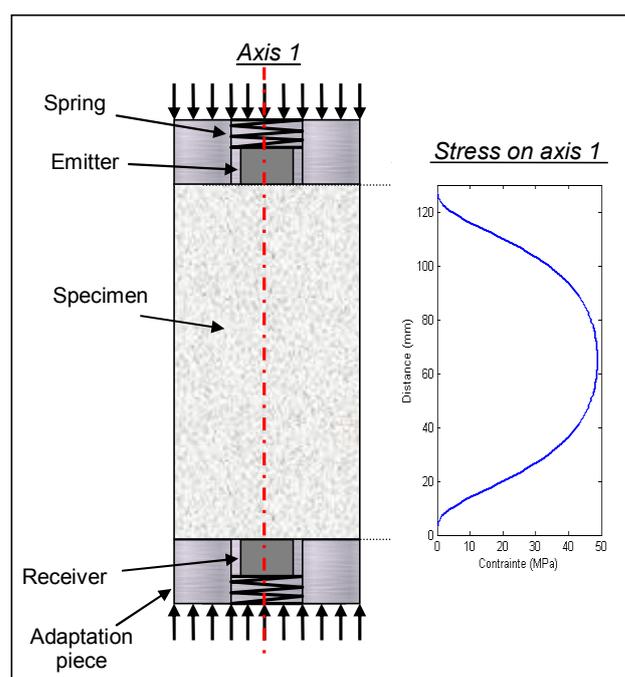


Figure 1: Loading setup.

This setup allows having a constant coupling stress on transducers by using compressive springs. A positioning preloading was moreover applied.

4.3 Ultrasonic measurement setup

Five kinds of wave were studied (cf. figure 2) for each specimen: two in loading direction (denoted P1 and "S1...") and three in direction perpendicular to loading (P2, S21 and S23).

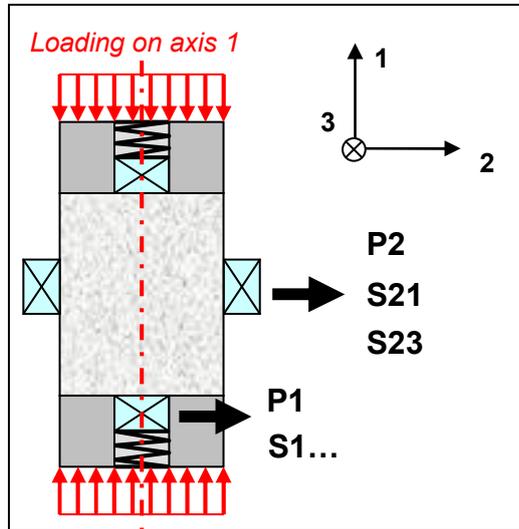


Figure 2: Configuration of ultrasonic measurements

Ultrasonic testing were realised using a Sofranel generator 5058PR, a Lecroy oscilloscope WS424 and ultrasonic broadband transducers (central frequency: 500 kHz). Presented measurements of velocities variations were obtained through cross-correlation processing between the reference signal with null stress and the acquired signal at each level of compressive stress.

5 Mechanical and ultrasonic results

5.1 Behaviour laws

Experimental behaviour laws were plotted from acquisitions of strain gages for tested specimens and materials. On each law models were identified from non linear regressions (cf. figure 3).

These works displayed a non linear behaviour during loading rise. Hysteretic behaviours and plastic strains after loading decrease were also observed according to the stress level (for maximum stress upper 30% of Rc). These specimens certainly present damage linked to these strains.

5.2 Ultrasonic velocities variation

We present in this paragraph experimental results concerning velocity variations of the medium subjected to stress versus the medium with null stress.

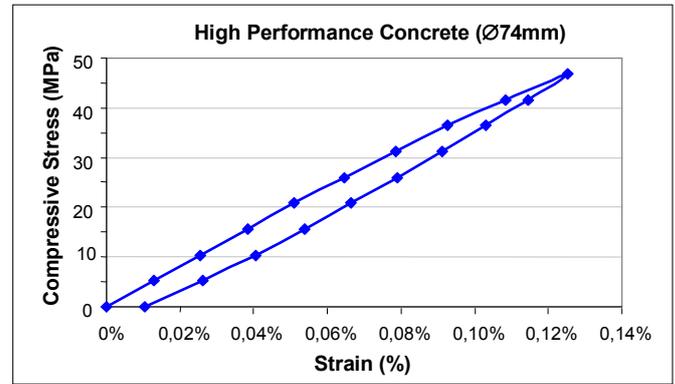


Figure 3: Experimental behaviour law of concrete

As expected from previous works, the most sensitive waves to the stress are: 1) pressure mode propagating in loading direction (P1) and 2) shear mode polarised in loading direction (S21). Moreover only little difference is observed between loading rise and decrease (little or no hysteresis) or a weak shift between start point and end point that is not significant (for example a shift of 0,03 % for S21).

That is why the following figures (figures 4 to 6) will only present results concerning these two modes with only loading rise curves. Then we will detail the behaviour of these two modes as a function of the stress variation in the various tested media.

Velocity variation curves for mortar specimens (figure 4 for diameter 74 mm) systematically present an increase of velocity with the stress whatever dimensions of the specimen. Moreover obtained variations enable to conclude about the existence of a non linear behaviour of mortar. One must also note that relative variations are widely higher than polycrystalline materials such as steel [12].

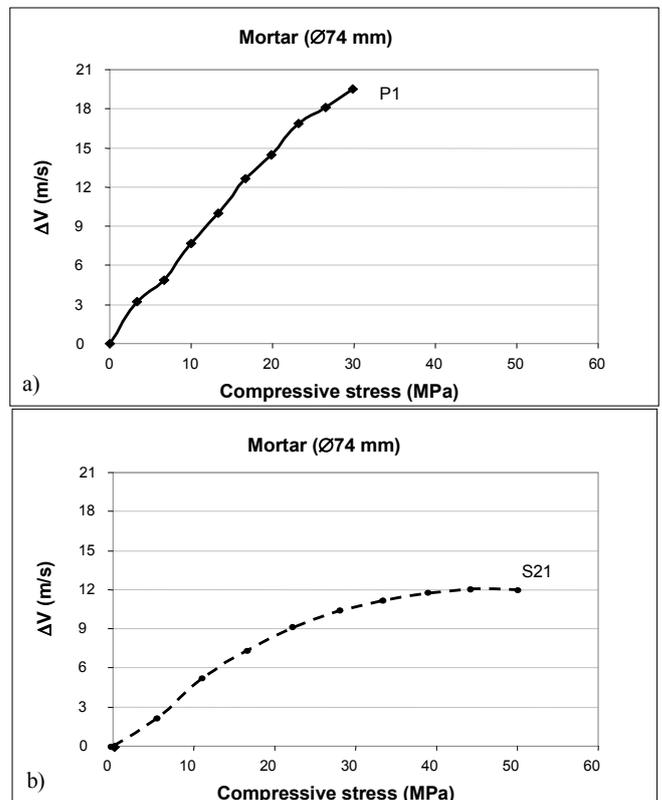


Figure 4: Velocity variations of a) pressure wave (P1) and b) shear wave (S21), versus stress in mortar

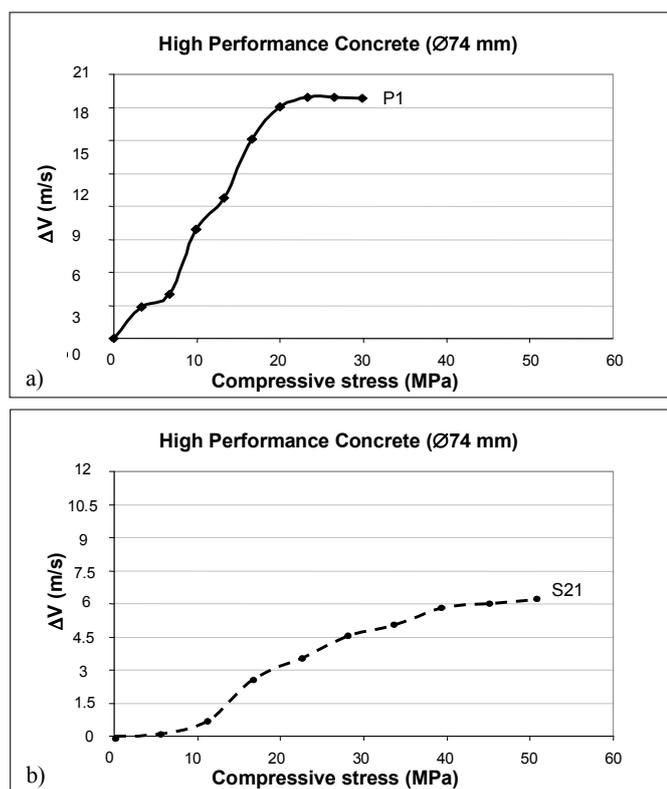


Figure 5: Velocity variations of a) pressure wave (P1) and b) shear wave (S21) versus stress in HPC

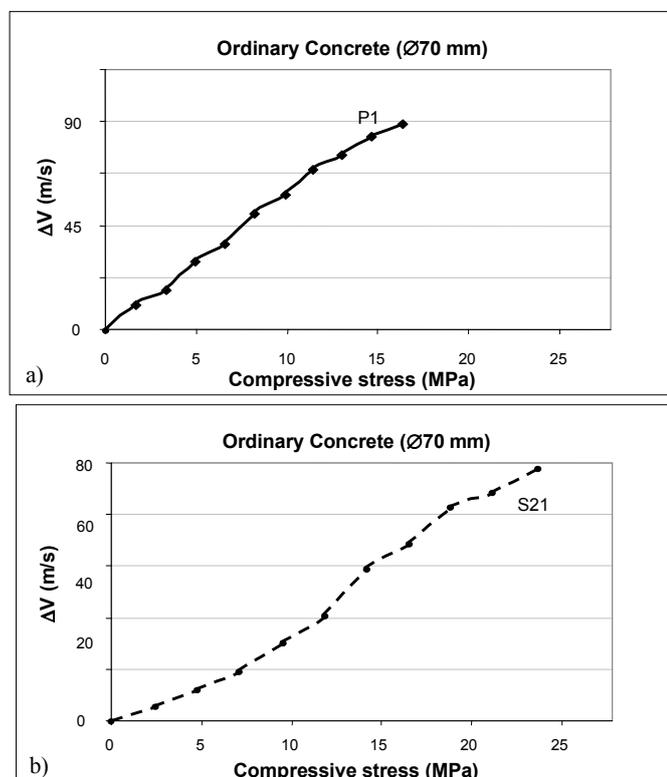


Figure 6: Velocity variations of a) pressure wave (P1) and b) shear wave (S21) versus stress in Ordinary Concrete

Curves obtained for the different concretes (figures 5 and 6) are globally similar to those for mortar. They present an increase of the velocities with the applied stress. For a given level of stress curves display a difference of variation amplitude of velocity as a function of the medium (at 10

MPa, for pressure wave, ΔV is about 8 m/s for mortar, 10 m/s for high performance concrete and 52 m/s for Ordinary concrete).

Obtained variations allow concluding to the presence of a non linear behaviour of mortar and concrete. One can also note a variability of the evolution dynamic as a function of the composition; non linearity of ordinary concrete is more pronounced than the HPC ones.

These different observations are certainly linked to multiple scattering that occurs in concretes and to the differences of acoustoelastic behaviours inside aggregates versus behaviours inside cements and mortars.

6 Conclusions and prospects

Bibliographic study showed the difficulty to model the mechanical behaviour of concrete in general. It also displayed the lack of acoustoelasticity testing in concrete in the literature.

Experimental study clearly proved that ultrasonic velocity varies as a function of uniaxial stress applied to concrete. The most sensitive waves to this stress are pressure waves and shear waves polarised in the loading direction. Acoustoelasticity measurements show that concrete can be 10 to 100 times more "acoustoelastic" than steel. Nevertheless obtained values of velocity variation are weak towards difficulties of measurement in this medium. So this technique seems to be hardly transposable in situ.

In return a measurement using the technique of Coda analysis (end of temporal ultrasonic signal) can be operated and enables on the one hand to avoid the need of distance value and on the other hand it leads to time variation measurements for important because measure is performed later in the signal. We show in a current study that this technique presents a real potential in situ.

This first study clearly shows that the evaluation of stresses in concrete is hard to perform nowadays in situ. The solution to answer this problem is to be interested on new technologies such as Coda analysis or non linear acoustics.

Acknowledgements

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