Analysis of coherent surface wave dispersion and damping for non-destructive testing of concrete

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Abstract

The durability of concrete structures is a major issue in civil engineering. Cover concrete monitoring is particularly important as it is in direct contact with the outside. High frequency surface waves (50-200 kHz) are adapted to provide information about this part of concrete, since they investigate materials at a depth close to the wavelength.

The high degree of heterogeneities in concrete is due to the presence of aggregates and pores of various sizes and shapes. As a result the waves propagate in a multiple scattering regime. Each signal is composed of a coherent part, resisting to averaging on disorder, and an important incoherent part, specific to the particular configuration of heterogeneities. This incoherent part leads to important mis-evaluation of the parameters of propagation of the waves. Average on several realizations of disorder are necessary to obtain the coherent field describing an equivalent homogeneous medium.

A laser interferometer is used to perform numerous measurements on different series of concrete and mortar slabs. The coherent field for each series is evaluated and effective parameters of the propagation (dispersion curves and damping factor) are estimated. The results show the sensitivity with granulometry (multiple scattering), but also with the water/cement ratio. This method appears to be suitable to monitor changes in porosity.

Résumé

La durabilité des structures en béton est un enjeu primordial en génie, civil. Le suivi du béton d’enrobage est particulièrement important, car cette partie est directement en contact avec le milieu extérieur. Des ondes de surface à hautes fréquences (50-200 kHz) permettent d'obtenir des informations sur cette partie du béton, car la profondeur d'investigation est de l'ordre de la longueur d'onde.

Le grand degré d’hétérogénéité du béton est dû à la présence de granulats et de pores de différentes formes ou dimensions. Les ondes se propagent donc en régime de diffusion multiple. Chaque signal peut être décomposé en une partie cohérente, qui résiste à la moyenne sur le désordre, et une partie incohérente, spécifique à une configuration particulière d'hétérogénéités. Cette partie incohérente induit des erreurs importantes dans l'évaluation des propriétés de propagation. Il est alors nécessaire de réaliser une moyenne sur différentes configurations du désordre, pour obtenir le champ cohérent, décrivant un milieu homogène équivalent.

On utilise un interféromètre laser pour acquérir de nombreuses mesures sur différentes séries de bétons et mortiers. Le champ cohérent pour chaque série est évalué et les paramètres effectifs de propagation (courbes de dispersion et amortissement) sont estimés. Les résultats montrent une sensibilité à la granulométrie et au rapport eau/ciment. La méthode peut permettre de suivre une évolution de la porosité.

Keywords

Ultrasound, scattering, effective medium, laser interferometer, Rayleigh waves
1 Introduction

Concrete structures are subjected to aggressive attacks from the outside (water, chlorides, weathering variations, ...) which may minimize their durability. In particular, near surface concrete is directly in contact with these aggressive attacks. This cover concrete thickness is 30-50 mm and it essentially protects the steel reinforcing bars from corrosion. An early diagnostic of the pathologies of cover concrete may prevent expensive repairs. The use of ultrasonic waves is of great interest to evaluate mechanical properties. Velocity and attenuation of such waves can be used to determine the viscoelastic properties (Young Modulus, Poisson ratio, Lamé coefficients), and also to characterize micro-structural properties of materials (porosity, grain size, micro-cracks).

However, precise measurements and their interpretations are difficult due to the inherent strongly heterogeneous nature of concrete. Concrete is basically composed of a mix of cement, sand, water and coarse aggregates. Sand are small particles with a mean diameter below 4 mm, while aggregates are the largest particles with dimensions varying from a few millimeters up to 20 mm or larger. Mortar can be distinguished from concrete because it contains only the small particles (sand, cement, water) without the coarser aggregates. Mortar and concrete also contains pores and capillaries. Porosity of this cement paste material can be linked with the water to cement ratio by mass ($w/c$) of the mix proportions of the concrete. All these heterogeneities of various size range strongly affect the propagation of ultrasonic waves, their influences depends on the frequencies used.

Experimental studies with compression waves [1,2] show that the influence of small air voids (<1 mm) and small sand particles (<4 mm) on the velocity or the damping factor at low frequencies (<500 kHz) is low. It is shown by [3,4] that only coarse aggregates with a diameter greater than 5 mm have a significant influence below 200 kHz. Surface measurements may also be used [5]. Rayleigh waves are adapted to the characterization of near surface deterioration of concrete, as their penetration depth is close to the wavelength. They are suitable to provide information about the first centimeters of concrete. Moreover, they are more convenient for on-site measurements than through-transmission measurements, since most concrete structures are accessible only on one side.

All studies show the influence of the heterogeneities in different frequency range. The objective of this paper is the evaluation of cover concrete with Rayleigh waves. The depth of penetration being close to the wavelength, to investigate the first centimeters of concrete, frequencies over the range 50-200kHz will be used, providing wavelength from about 10 to 50mm. In this frequency range, the effect of pores and small particles (<5 mm) is mainly observed as an absorption losses than an multiple scattering process, but coarser aggregates will interact strongly with the waves.

This paper introduces the process needed to focus on global properties of concrete. Experimental configuration and acquisition setup is described. Then results for various concrete and mortar are given.

2 Homogeneous effective medium

Concrete can be considered as a random distribution of scatterers (aggregates) of different nature, shape and size in a cement matrix. Waves propagating in such media with a wavelength comparable to the size of scatterers will propagate in a multiple scattering regime. The measured signals will be composed of a coherent part, and also of an important incoherent part specific to the given configuration of heterogeneities encountered [6].

It is possible to take into account the randomness by considering the average value of the measurements over a statistical ensemble of collections of scatterers. This notion was introduced by Foldy (1945) [7]. This coherent field can be interpreted as the field propagating in an equivalent homogeneous medium (effective medium).
In order to evaluate the mechanical properties of concrete, studying a single realization of disorder will lead to inaccurate results. As the signal contains an important incoherent part, the results will mainly depend on a specific configuration of aggregates, and not on the general properties of the concrete. The evaluation of the coherent field will eliminate the incoherent contributions and focus on the effective medium. In this case dispersion curves and damping factor of the field will provide information which can be interpreted as the average mechanical properties of the concrete.

To evaluate this coherent field, it is then essential to perform measurements on numerous equivalent realizations on disorder, i.e. at different positions on the tested sample of concrete, using the same source and the same receiver and at the same distance of propagation.

3 Experimental procedure

3.1 Concrete slabs
The measurements are carried out on concrete slabs of 60 x 60 x 12 cm$^3$. There are two different series of concrete with different w/c and a maximum grain size ($D_{\text{max}} = 20 \text{ mm}$). Two series of mortar ($D_{\text{max}} = 4 \text{ mm}$) are made with the same w/c than concretes. The characteristics of each series are summarized in table 1. Each series is composed of 5 slabs.

In order to guarantee a constant water content of the concrete slabs, they are stored immersed in water with additional lime. The water content ratio of the slabs is then close to 100%. The slabs are taken out of the water only during the measurements. When the measurements were performed, the slabs have an age between 6 and 10 months, and the mechanical properties of concrete are assumed to be stabilized.

<table>
<thead>
<tr>
<th>Table 1. Characteristics of each series of concretes and mortars</th>
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<td>Concrete $D_{\text{max}} = 20 \text{ mm}$ w/c = 0.35</td>
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<tr>
<td>--------------------------------------------------------</td>
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<tr>
<td>B1</td>
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<td>Mortar $D_{\text{max}} = 4 \text{ mm}$</td>
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3.2 Experimental setup
Rayleigh waves are generated with a piezoelectric transducer (Imasonic). The transducer emits a compression wave and is equipped with a wedge to allow an incidence with the concrete slab at an angle favoring the conversion to Rayleigh waves [8]. The wedge is coupled with the concrete with Gel D (Sofranel) over a thin scotch-tape. The scotch-tape avoids the gel to penetrate into the concrete. The center frequency of the transducer is 120 kHz. It is excited with a Ricker wavelet amplified by a Ritek Gated RF amplifier. The bandwidth at -20dB of the emitted Rayleigh waves ranges from 60 kHz to 180 kHz.

The reception is performed with a laser interferometer (Tempo by BossanovaTech), allowing non contact and point-like acquisition of the normal displacement of the surface. A reflecting tape on the concrete enhance the quality of the signals. The interferometer is mounted on an automatic bench and moved along a line in front of the transducer to have measurements at different distances $d_i$ from 10 to 45 cm (Fig.1). The first reception point is at $d_i=10 \text{ cm}$ from the source to avoid near offset effects. The whole profile is composed of $N_r=36$ signals, every $\Delta d=10\text{ mm}$. To reduce the signal to noise ratio, each signal is time-averaged over 256 acquisitions at each reception point.

To acquire different configurations of disorder, 9 parallel profiles, separated of $L=40\text{ mm}$, are acquired on both sides of the slabs. $L$ was chosen so that $L>D_{\text{max}}$ and $L > \lambda_{\text{max}}/2$ to ensure that profiles are not correlated. We acquire a data-set of 90 different multi-station profiles for each concrete series. Only 36 profiles were acquired for mortar as the heterogeneities are too small to generate an important incoherent part for the frequencies considered.
4 Coherent field and signal processing

4.1 Obtention of the coherent field

Before evaluating the coherent field, preprocessing have to be undergo to eliminate artifacts due to the experimental setup. The geometrical spreading of Rayleigh waves in $1/\sqrt{d}$ is corrected. Each profile is normalized by the maximum amplitude of its first signal in $d_1$, to eliminate the variations due to the difference of coupling of the transducer to the slabs. At last, as $d_1$ slightly varies from one profile to the others due to the hand positioning of the source transducer, the time lags induced are evaluated and corrected.

Fig.2-(a,b) presents two seismograms for two given profiles on a concrete slab of series B2. All signals present an important incoherent part that fluctuates from one seismogram to the other. The coherent field for each series is obtained by spatially averaging the different equivalent realizations of disorder. The coherent field for series B2 is presented in figure 2-(c), incoherent contributions to the field are no longer visible and two main wave trains can be noticed. The first one is the most important and corresponds to the coherent Rayleigh wave. The second one corresponds to a reflection of the wave emitted by the transducer inside the wedge. To eliminate this reflection, the main wave train is windowed with a Hann window.

4.2 Signal processing methods

Signal processing tools are inspired from classical geophysics methods. The phase velocity $v_{\phi}(\omega)$ is computed using the $p-\omega$ transform which represents the entire data wave field into the slowness-frequency domain, where $p=1/ v_{\phi}$ [9]. The damping factor $\alpha(\omega)$ is estimated from the decrease of the amplitude spectrum of the coherent field during the propagation. Estimation of group velocity $v_g(\omega)$ provide complementary information on the propagation. Group velocity is obtained through Reassigned Multiple Filter Analysis [10].

The use of these signal processing tools impose requirements on the position of the reception points $(N_r, \Delta d)$. Experimental setup used in this study was designed to take account of all these artifacts and to provide accurate measurements in the bandwidth 60 kHz-180 kHz.
5 Results and discussion

Dispersion curves for phase and group velocities of the coherent field are plotted in Fig 3. Concretes are represented with empty items (Δ,○) and mortars by filled items (▲,●). Triangles, correspond to w/c=0.65 and circles to w/c=0.35. For a give w/c ratio, the presence of aggregates increases the velocity of about 10%. Higher w/c induces lower velocities, as high w/c corresponds to high porosity and hence lower mechanical strength.

When the porosity is high, the coherent phase velocity presents a characteristic decrease of variations of properties of the material with depth. This occurs either on B2 and M2 and it is remarkable that it is not noticeable on B1 and M1. This phenomenon is then linked with the w/c and the porosity and may be explained by a variation of porosity with depth.

Effective group velocities dispersion curves for mortars are quite constant with frequency, but the presence of aggregates in concrete induces particular variations, not noticeable on the phase velocity. Both phase and group coherent velocity measurements provide complementary information.

Effective damping factor curves are plotted on Fig.4. For mortars, where multiple scattering effects are not important, the damping factor curves are almost linear with frequency. A higher w/c (higher porosity) logically induce higher attenuation. When aggregates are present, the effect of scattering are combined to other effects. Contributions of multiple scattering can be deduced by comparing mortar and concrete sharing the same w/c. At low frequencies (<100kHz), no difference is visible between a concrete and its corresponding mortar. At higher frequencies, scattering effects become important and the damping factor increases. For low w/c, this increase is relatively low (1 Np.m⁻¹), but at higher w/c the effects are very important. As B2 and B1 share the same kind and quantity of aggregates and differ only with their w/c, multiple scattering does not only depend on the amount and size of scatterers, but also on the w/c. An explication may be the presence of an important interfacial zone between aggregates and mortar when the porosity is high, which increases the effects of the scattering by the aggregates.
6 Concluding remarks

Surface waves are adapted to characterize cover concrete. The accuracy of the estimations of the propagation parameters $v_\phi$, $v_g$, and $\alpha$, is primordial, as many phenomena are involved in the propagation. Appropriate signal processing tools for the treatment of Rayleigh waves are used and particular attention has to be drawn to the acquisition setup required by these tools. Another key point is the use of coherent waves, obtained by averaging the signals over a large amount of configurations of disorder.

A better understanding of the propagation in such complex media is needed, to be able to evaluate mechanical parameters (Young modulus, Poisson ratio, porosity). In particular, a model of the multiple scattering in concrete have to be studied to distinguish the attenuation process due to scattering and the one due to porosity or viscoelasticity [11,12].

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References