Computation and experimental considerations on dynamic testing of cement mortar

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Abstract. Non-destructive tests to assess the dynamic characteristics of the materials are important for both in-situ and laboratory situations. Elastic modulus, rigidity modulus and Poisson ratio can be determined through dynamic testing, by employing resonant frequency measurements. The ASTM C-215 standard contains the necessary information for the experimental set-up and subsequent computation using the longitudinal, transversal and torsional frequencies, for both prismatic and cylindrical specimens. Nevertheless, some experimental particularities are not explained and their influence on the final results might prove important. In this paper, the experimental and computational insights on performing the dynamic Young modulus test for cement mortar prismatic samples, with emphasis on the importance of interpretation of the results are presented. The type of specimen support and the actual data manipulation, when extracting results, are taken into consideration. The results may prove important for the correct employment of dynamic testing.

1. Introduction
Elastic modulus of building materials is a key characteristic, with the structural design process heavily relying on its value. For concrete, it is usually determined by a static method, which implies repeated measurements of the strain when increasing the compressive force from zero to maximum 40% of the compressive strength [1][2]. This could also be done for mortar but it is much more challenging due to its much lower compressive strength [3].

Non-destructive, dynamic, methods have been used for both concrete and mortars [3]–[5]. Vibrational tests can be employed for determining the modulus of elasticity, modulus of rigidity and the damping properties by measuring the resonance frequency of the specimen and the propagation of a signal through it. These tests can be done by:

- forced oscillations, where a signal of constant amplitude and increasing frequency is induced in the specimen by means of a shaker; the natural frequency to be used in computing Young’s modulus will be noted when the response of the sensor attached to the specimen is maximum.
- impact resonance method, where an impact on the specimen produces a signal, and the free, decaying, vibration is used to identify the resonance (FFT analysis).

The values obtained via this route for Young’s modulus are significantly higher than those obtained through static tests but empirical correction equations have been determined in order to correlate the results from both dynamic and static approaches [8].

The purpose of the present research is to show the particularities of employing the impact resonance dynamic test approach when used on mortar prismatic samples and how to correctly assess the elastic modulus from the obtained data during the experiment. The impact method presents some advantages
over the forced oscillations method. Firstly, it does not need a special device to create the oscillations (usually a shaker powered by a power amplifier and a frequency generator), which can be quite expensive and can induce errors due to the large frequency range needed in the experiments on concrete and mortar specimens (0-2kHz). Secondly, the measured decaying signal can be used to assess the damping properties of the material.

2. Experiment

2.1. Materials

Mortar samples have been prepared with a classical mix to accommodate a M10 strength class. The mortar was cast in metal moulds, following EN 1015-11 guidelines, obtaining prismatic specimens with 40 × 40 × 160 mm dimensions (width × height × length). The specimens have been further put in water and cured for 28 days.

2.2. Dynamic characterisation

The impact resonance dynamic test, as described in the ASTM C215-14 standard [9] was used. This type of test can be easily performed both in the laboratory and in-situ. Nevertheless, the data interpretation can be challenging, especially when not using a commercially developed apparatus for this specific purpose.

The focus was on the longitudinal geometry. The specimen was supported in the middle. However, ASTM C215-14 code does not give any details related to the width of the support. For this reason, two support widths were used to see the influence of this parameter: t_{narrow}=2cm and t_{wide}=5cm. Also, an innovative approach to reduce unwanted influences from outside sources was tested. The specimen was placed in a vertical position on a material with damping properties. The set-up layouts are presented in figure 1.

![Figure 1. Experimental setup for longitudinal resonance test: a) classic, b) vertical.](image)

Following this experiment, Young’s modulus can be computed using equation (1). The result is expressed in [Pa].

$$E_d = D \cdot m \cdot f_n^2$$  \hspace{1cm} (1)

where:

- $D = 4 \frac{L}{b \cdot t}$, in [m^{-1}], is a constant related to the length (L) of the specimen and the cross-sectional dimensions (b, t); this equation is applied for a prismatic specimen only.
- $m$, in [kg], is the mass of the specimen.
- $f_n$, in [Hz], is the natural longitudinal frequency that is measured during the experiment.
3. Results

The geometric dimensions and the mass of the prismatic sample have been measured (table 1), in order to perform the calculations of the elastic modulus as shown in equation (1).

| Property                  | Value         |
|---------------------------|---------------|
| mass [kg]                 | m=0.533       |
| length [m]                | L=0.160       |
| cross-section dimensions [m] | b=t=0.04     |

The longitudinal impact experimental setup is described to use a support at the middle of the specimen, as shown in figure 1. Nevertheless, the characteristics of this support are not given (width, material etc.). The position of the support is chosen to coincide with the node of the longitudinal vibration, in order to allow the signal to pass freely through the specimen. Due to practical considerations, it is unlikely to effectively use a thin enough support, as it would be desired. Also, the position of the node at the geometric middle of the specimen depends on two things that are supposed to be true but might not be: i) the impact is done exactly in the middle of the cross-section; ii) the specimen is a perfect rectangular prism.

During the first experiment, the specimen on a narrow wood support (t=2cm) was tested. This width represents around 12% of the length of the prism. It was the smallest width that did not present significant challenges in practice. Wood was chosen as the support material (and it was used for the next experiments also) since it has vibrational properties quite different from those of the cement mortar.

In figure 2a), an example of the resulting impact for the first experiment is presented. There is a vibration that modulates the traveling signal through the specimen for more than half the time. This can be explained by the relatively low weight of the mortar prism when compared to: i) the accelerometer and its connector (which were around 80g); ii) the impactor (close to 100g). The wave could be attributed to the mechanical movement (displacement) induced in the specimen during the impact and to the resonance of the impactor. Towards the end of the signal, the natural vibration can be observed unaltered, thus the resonant frequency can be inferred. Nevertheless, the damping properties of the material are obstructed by the damping of the modulating wave when the full signal would be considered and the unaltered part is too small to be usable for this purpose.

Subsequently, to reduce any possible hinge effect, a wider support was used. The width of 5cm accounts for more than 30% of the specimen length. The result in figure 2b) shows a big improvement, but the modulating signal is still very important in terms of damping characteristics.

Following this improvement, the specimen was fully rested on a wooden support. The result presented in figure 2c) shows a considerable degradation with the initial modulation existing throughout most of the signal. Moreover, the support starts to act as a secondary source of vibration, as it can be observed after the first complete decay of the impact signal.
Figure 2. Impact signals through the specimens: a) narrow support; b) wide support; c) full support.

The experimental program pursued to improve these tests by vertically positioning the specimen, thus completely removing the influence of the support. The result is superior to all previous tests, with the damping of the impact signal unmodified by the modulating wave, as shown in figure 3.

Figure 3. Impact signal in vertical position

The signal in all situations was analysed by fast Fourier transform (FFT). In every case, both the whole signal and the final, unmodulated, part were considered. It is important to compare the two types
of assessments, as it may be a source of error to examine too much or too little of the signal. The FFT was used to quantify both the position and the width of the resonance peaks. While the position is important for computing the dynamic modulus of elasticity, the width is related to the damping properties of the material, with a wider peak indicating more damping.

The analyses of the experiments based on supporting the specimen are presented in figure 4.

The FFT of the experiment involving the narrow support shows that the full signal contains a lot of frequency components (figure 4a). Two big peaks can be observed, at around 2 kHz and 12 kHz, respectively, and many smaller ones. Performing the analysis on the unmodulated part of the signal, at the end, two components are clearly visible (figure 4b). The 12 kHz frequency remains the higher peak in the plot, indicating it as the longitudinal resonant frequency (as expected for cement mortar specimens this size and composition). The second highest peak that can be observed is situated at around 5 kHz and can be related to the transversal mode of vibration (additional experiments – not shown here – have been performed to check for this fact). The presence of the transversal component can be related to the error in hitting the specimen. The selected signal can be seen to retain a small part of the modulating signal at around 2 kHz. An important observation related to the width of the longitudinal resonance peak, which differs greatly in figure 4a) and figure 4b), making the damping assessment unreliable in this case.

The wide support setup, which results in a cleaner signal over a longer period of time, shows the resonance to be positioned close to the same value as before. As expected, the modulating signal is less well established in the FFT plot, even when considering the full signal. The profiles in figure 4c) and 4d) are both slim, pointing towards a viable damping assessment.

Resting the specimen fully on the support does dampen the modulating signal, but the error is higher when compared to the wide support. Also, the peaks have somewhat different profiles when comparing the full signal and a selected one.

The narrow support and the full support presented the same problems when comparing peak profiles. This can be assigned to the fact that the selected signals in both cases were a small portion of the whole measurement. Restricting the analysed part was due to the big error induced by the modulating signal.

The vertical placement has the most consistent results in terms of FFT analyses (figure 5). Almost all of the measurement contains the natural vibration within the specimen. The transversal frequency was present, but not dominant. It can be removed with more careful positioning of the specimen but it was not detrimental to the fundamental longitudinal value.
Figure 4. FFT results of experiments employing a wooden support: a) narrow support (full signal); b) narrow support (selected signal); c) wide support (full signal); d) wide support (selected signal); e) full support (full signal); f) full support (selected signal).

Figure 5. FFT analyses for the vertical position experiment: a) full signal; b) selected signal.

All FFT plots have been used to obtain the fundamental longitudinal frequency by analysing the peaks. A peak fitting operation has been performed, in order to reduce the errors given by the measuring devices. The fit has been done using a Voigt profile in order to take into account both machine and process peak widenings and displacements.
An example is given in figure 6 and the results for peak positions are given in table 2. Moreover, the full width at half maxima (FWHM) is obtained during this fitting, and it can be used to approximate the damping coefficient (noted $dc$) of the material applying equation (2).

$$dc = \frac{FWHM}{2f}$$  \hspace{1cm} (2)

The results are consistent in terms of elastic modulus. Most experiments provide a value within the 31.6 – 31.7 [GPa] interval. Notably, the wide support and vertical experiments are the most coherent, as expected. The damping coefficient varies significantly in the experiments employing a narrow support and a full one. The vertical measurement shows the most promising result, since the analysis on the full signal and the selected one gives almost the same value.

![Figure 6. Example of peak fitting result](image)

**Table 2.** Longitudinal resonance test results

| Support   | Signal | $f$ [Hz] | FWHM [Hz] | E [GPa] | $dc$ [%] |
|-----------|--------|----------|-----------|---------|---------|
| narrow    | full   | 12114    | 165       | 31.63   | 0.68    |
| narrow    | selected | 12119 | 595       | 31.65   | 2.45    |
| wide      | full   | 12128    | 72        | 31.7    | 0.29    |
| wide      | selected | 12128 | 92        | 31.7    | 0.37    |
| full      | full   | 12124    | 185       | 31.68   | 0.76    |
| full      | selected | 12138 | 306       | 31.75   | 1.26    |
| vertical  | full   | 12117    | 81        | 31.6    | 0.33    |
| vertical  | selected | 12123 | 84        | 31.6    | 0.34    |

4. Conclusions
An experimental program was conducted in order to assess the established procedure for the impact test method in the longitudinal configuration. Different supporting options are evaluated and an alternative to the prescribed arrangement is proposed. The validity of the proposed lay-out is demonstrated through data analysis of the impact signal. Testing the specimen in the vertical position gives the best results.
since no source of error and interference are present. For all other tests, the signal has been shown to have various components and proper investigation requires choosing the relevant segment of the recorded signal.

The proposed method presents advantages on both “fronts”: experiment and analysis.

First of all, the experiment is easier to perform (there is no need to choose a support – material, width, a.s.o.).

Analysis-wise, since most of the signal is “clean” there is no need for in-depth examination of the measurements. This makes it promising for future industrial applications, providing a facile procedure.

Due to the reliable nature of the experiment, it can also be viable in the investigation of the damping properties of materials.

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