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Measurement of concrete E-modulus evolution since casting: A novel method based on ambient vibration

Miguel Azenha [a,c,*], Filipe Magalhães [b], Rui Faria [a], Álvaro Cunha [b]

[a] LABEST – Laboratory for the Concrete Technology and Structural Behaviour, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[b] VIBEST – Laboratory of Vibrations and Structural Monitoring, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[c] ISISE – Institute for Sustainability and Innovation in Structural Engineering, Universidade do Minho, Escola de Engenharia, Campus de Azurém, 4800-058 Guimarães, Portugal

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ABSTRACT

The use of ambient vibration tests to characterize the evolution of E-modulus of concrete right after casting is investigated in this paper. A new methodology is proposed, which starts by casting a concrete cylindrical beam inside a hollow acrylic formwork. This beam is then placed horizontally, simply supported at both extremities, and vertical accelerations resulting from ambient vibration are measured at mid-span. Processing these mid-span acceleration time series using power spectral density functions allows a continuous identification of the first flexural frequency of vibration of the composite beam, which in turn is correlated with the evolutive E-modulus of concrete since casting. Together with experiments conducted with the proposed methodology, a complementary validation campaign for concrete E-modulus determination was undertaken by static loading tests performed on the composite beam, as well as by standard compressive tests of concrete cylinders of the same batch loaded at different ages.

1. Introduction

Concrete is a multiphase material that endures significant changes at micro-structural level along cement hydration. In the instants after mixing it consists of aggregates suspended in the cement paste, behaving nearly like a Newtonian fluid, which gradually evolves to a Bingham type material, and finally reaches a solid state [1]. Knowledge of how concrete E-modulus evolves since casting and along hydration reactions is of paramount importance for many fields of materials science, namely for the prediction of stress development in hardening concrete at early ages, when significant volumetric changes are known to occur (both due to thermal and autogenous shrinkage phenomena). It is therefore quite important to know the structural setting time (threshold instant at which concrete starts to bear structurally relevant stresses [2]), as well as the concrete stiffness increase along time.

Two dominant non destructive techniques for determination of the evolving concrete E-modulus have been used for quite some time: the resonant frequency and the ultrasound methods (both based on pulse velocity and wave reflection). The first one is widely spread, including in ASTM standards [3], and basically consists of impacting concrete specimens with hammers, and measuring their fundamental transverse, longitudinal and torsional frequencies, which in turn are related to the E-modulus of concrete. As the method requires a mechanical shock to create an excitation, it is applicable only after demoulding the specimen, so it requires concrete to be hardened (i.e., past structural setting) [4]. Therefore this requirement makes the technique inadequate to measure concrete E-modulus evolution just after casting (earliest evaluations were reported at the ages of 5 h [5] and 8 h [6]), as well as to determine the mechanical threshold.

One of the most adopted ultrasound techniques is based on the measurement of the velocity of propagation in concrete of artificially generated P or S waves, which is then related to the material E-modulus or other mechanical properties [7–10]. With adequate experimental setups, where emitter/receptor pairs are embedded into the specimen's formwork, it is possible to evaluate the sound wave speed continuously right after concrete casting. External disturbances that may cause parasite waves in the specimen, such as due to jackhammers, should be avoided during the test [4]. The use of pulse velocity measurements for direct estimation of elastic properties of concrete has been discouraged by Philleo [11,12], claiming that concrete does not fulfil the physical requirements for validity of the analytical equations that relate pulse velocity to E-modulus in homogeneous materials. Nonetheless, more recent studies have been made that point to the usefulness of pulse velocity measurements for estimating mechanical properties of concrete [13,14].

Early monitoring of concrete properties with ultrasound techniques can also be done with recourse to measurements of wave reflections. It basically consists in monitoring the reflection coefficient of ultrasonic waves at an interface formed by a buffer material and the concrete to be tested, and relating the measured reflection coefficient

* Corresponding author. ISISE – Institute for Sustainability and Innovation in Structural Engineering, Universidade do Minho, Escola de Engenharia, Campus de Azurém, 4800-058 Guimarães, Portugal. Tel.: +351 253 510 248.
E-mail address: miguel.azenha@civil.uminho.pt (M. Azenha).

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with the elastic properties of the hardening concrete (namely the shear modulus) [15–18]. This methodology has the advantage of allowing single face measurements.

Other non-destructive techniques for early age concrete exist that allow monitoring the evolution of the material stiffness or compressive strength, or determining the setting time. Among them, one can refer the methods based on nuclear magnetic resonance [19], on the electric properties of concrete [20–22], on impact-echo techniques [23,24] and on acoustic emission [25,26]. An extensive review of all these methods can be found in the RILEM report of TC185-ATC [27].

The present paper details a novel method that may be considered a variant to the traditional resonant frequency approach, devised in an original way to allow the continuous measurement of concrete E-modulus right after casting. For that purpose, an experimental setup that consists of a simply supported beam made up of an acrylic glass tube (polymethylmethacrylate), filled with fresh concrete, is presented. Then, and accounting only for the excitation induced by ambient vibration, the frequency of the first flexural mode of this beam is continuously monitored along time, so that: *(i)* just after casting concrete performs like a viscous fluid, thus at the beginning of the test the identified frequency corresponds to that of the acrylic tube carrying the mass of the unhardened concrete; *(ii)* during concrete hardening a composite behaviour is endured, and the first flexural frequency of the beam increases in correspondence to the growing concrete Young modulus.

This methodology combines the advantages of ultrasound techniques, being able to continuously measure E-modulus right after concrete casting, with the advantages of resonant frequency methods, which allow obtaining E-modulus upon determination of a structural characteristic (in the present case the first frequency of vibration). Also, the proposed method is entirely passive, with no necessity of providing external vibration sources. In fact, the ambient vibrations are enough: people walking nearby, cars riding adjacently to the building, mechanical equipment vibrations, wind acting on buildings, and so on.

This paper is organized in seven sections, being Section 2 related to the description of the experimental setup. Section 3 is devoted to a brief description of the principles of modal identification techniques based on ambient vibration. The results obtained with the proposed methodology, together with complementary experimental campaigns (which include compressive tests for E-modulus determination, as well as static load-deflection measurements at the beam mid-span), are presented in Section 4. Section 5 provides an interpretation and discussion of results, in view of the analytical relationships that allow obtaining the concrete E-modulus from the identified frequency under evolution. A further set of experiments comprising two other beams with the final recommended setup is described in Section 6, with the aim of showing the repeatability of the proposed method. Finally, Section 7 presents the main conclusions in regard to the proposed method.

2. Experimental setup and campaign

2.1. Composite beam — experimental procedure

The essential feature of the intended experiment consists of casting concrete inside an acrylic formwork, which is thereafter placed horizontally, working as a simply supported composite beam. Then, the first frequency of vibration f of this simple structural system is to be continuously monitored along the concrete hardening phase, as f is directly correlated with the evolving E-modulus of concrete.

The very first component of the experiment is then an acrylic hollow cylinder 2 m long and 4 mm thick, with an external diameter of 100 mm, depicted in Fig. 1. Several holes with a diameter of 5 mm were drilled in the cylinder (symmetrically in regard to the mid-span), with the following purposes: *(i)* two horizontal holes placed 100 mm from the edges, where steel rods are inserted to materialize the pinned supports, and *(ii)* a series of vertical holes at each 300 mm from the beam supports, where rods are installed to act as connectors, improving acrylic-concrete composite behaviour. The horizontal rods referred in *(i)*, which consist of 4 mm diameter threaded steel bars with a Young's modulus of 180 GPa, materialize the pinned supports by trespassing the cylinder, and spanning 150 mm between the flanges of two HEA steel profiles placed laterally at the beam ends, as schematized in Fig. 1 and reproduced in Fig. 2. Since the distance between the HEA flanges and the external diameter of the acrylic cylinder differ from 50 mm, in this arrangement each horizontal rod *(i)* actually performs as two ‘small cantilevers’, with a span of 27 mm each, transferring the support reactions to the composite beam (the length of 27 mm corresponds to the distance between the centre of the supporting flange and the mid-thickness of the acrylic formwork). Flexibility of these ‘small cantilevers’ played a role in the results obtained, as to be discussed later. Furthermore, due to a slight 4 mm lateral misplacement of the beam over the HEA profiles, a situation occurred in which the ‘small cantilevers’ ended up unequal, with spans of 23 mm and 31 mm (subject to be addressed later also).

The accelerometer adopted, weighting 2.27 kg, was fixed at mid-span on top of the beam (see Fig. 2), using the local vertical rod *(ii)* and two symmetrically placed polystyrene saddles.

Concrete casting started with the acrylic cylinder inclined at a 45° angle with the horizontal, ending with the tube in vertical position for placement of the closing lid. The time elapsed between onset of casting and the start of acceleration acquisition was less than 15 min. During the whole monitoring period, which extended for 14.9 days since casting, the composite beam remained untouched inside a climatic chamber, under a constant temperature of 20 °C and a relative humidity of 50%. Bearing in mind the observed influence of the supporting horizontal rods on the measured frequencies, at the age of 14.9 days the experiment was interrupted, and the supporting conditions were changed by suppressing the ‘small cantilevers’, enforcing from then on vertically rigid pinned supports (see Fig. 3).

After this support condition was changed some periods of ambient vibration measurement were performed until the age of 15.08 days. The experiment was then interrupted and left untouched, and at the age of 28 days additional experiments were performed (without any further change to the support conditions). Firstly, a time series of 15 min duration was recorded, in order to identify the beam frequency f at this age. Then a static loading test was performed, where steel plates with known mass were sequentially placed on top of the accelerometer (at mid-span), and the corresponding mid-span deflections were recorded with Linear Variable Differential Transducers (LVDT). After this static test, which was conducted with loads well below the cracking load of the beam, nine time series of 15 min duration each were recorded, in order to check that f remained the same, and that no damage was induced to the composite beam.

In parallel to the beam tests, and for comparison purposes, concrete E-modulus was also evaluated through standard compressive tests performed on cylinders (15 cm diameter, 30 cm tall) at the ages of 0.75, 1, 2, 3, 7 and 28 days, cast with the same concrete batch, and using three specimens per age. Prior to testing all specimens were kept on an environment with a temperature of 20 °C and a relative humidity of 100%.

2.2. Materials and mixture proportions

For the pilot experiment in this paper a self-compacting concrete with a water to cement ratio of w/c = 0.42 was selected, with the mixture proportions provided in Table 1. River sand and crushed granite stone were used, and the maximum aggregate size was 16 mm.

The acrylic used for the formwork was obtained by extrusion, and a summary of its main properties can be found in Table 2.

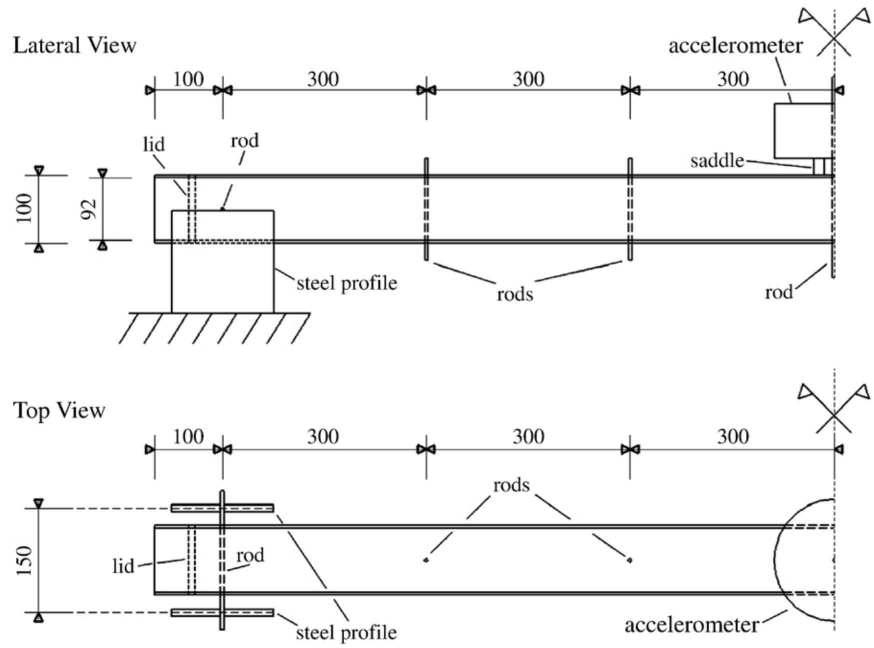

Fig. 1. Geometry of the acrylic tube (in mm) and experimental setup.

3. Monitoring natural frequencies using ambient vibration tests

The use of the ambient vibration technique to characterize the dynamic behaviour of civil engineering structures is a subject that has been widely exploited since the 1960's. Ambient vibration tests have the strong advantage of using freely available excitation sources, like the wind, the traffic over a bridge or the ground vibrations induced by the activities in the surroundings of the structure under study.

In this work the equipment and processing routines usually applied in field tests of large civil structures [28], or in the context of Dynamic Monitoring programs [29], were used in the laboratory test of the described simply supported beam, to track the evolution of its first natural frequency *f* along the early age hardening of concrete. The use of ambient vibration implies that the levels of measured responses are very low, so the applied sensors must have high sensitivity and low noise level, and the measuring system should provide a good resolution. In the pilot experiment considered in this paper a CMG-5T force balance accelerometer from Guralp was used, which allows measurement of accelerations within the frequency band from approximately 0 up to 100 Hz, having a sensitivity of 5 V/g and a noise floor around 2 μg. This sensor was connected to a GSR-24 recorder from Geosig that provides power to the sensor, performs the analogue-to-digital conversion of the measured signals using a 24-bits board, and stores the collected data in an internal memory card. The recorder was programmed to perform the acquisition of 15 min time series with a sampling frequency of 100 Hz, according to a predefined timetable. Fig. 4 presents a picture with all the equipment used for the dynamic measurements.

The acceleration time series collected by the dynamic acquisition system were processed with MATLAB routines, in order to perform the identification of the dominant frequencies and track the evolution of the first resonant frequency of the composite beam. For the present application closely spaced natural frequencies are not expected, and identification of other modal parameters is out of scope. Accordingly a relatively simple identification methodology was used, based on evaluating spectral estimates of the ambient structural responses from the measured time series. This can be done using the Welch procedure [30], which involves the following steps: *(i)* division of the response records in several segments (eventually with some overlap); *(ii)* application of a signal processing window to the data segments to reduce leakage; *(iii)* computation of the Discrete Fourier Transform (DFT) of the windowed segments; *(iv)* computation of the auto-spectra using the DFT of the windowed segments; and *(v)* averaging the spectra associated to each time segment. For the present application the spectra were estimated using time segments with

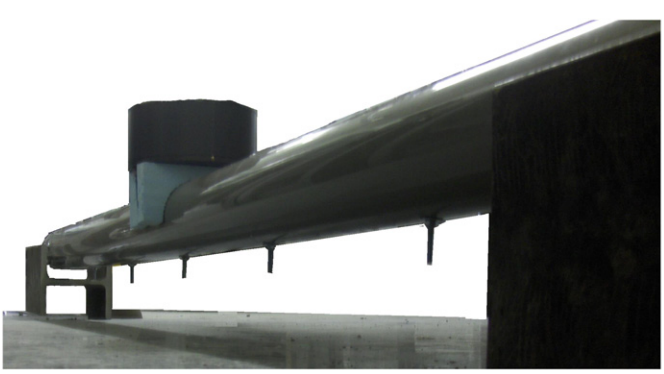

Fig. 2. Photo of the experimental setup.

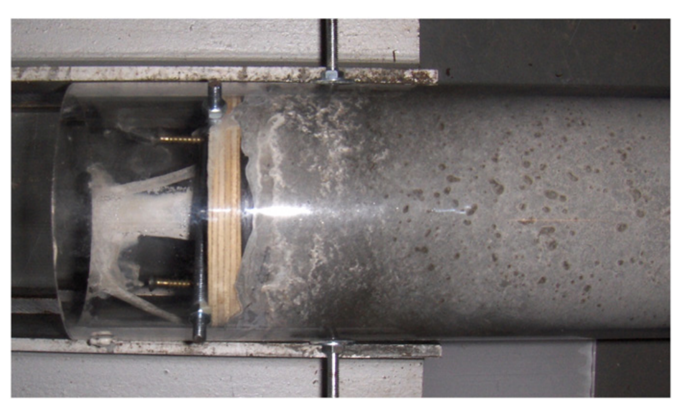

Fig. 3. Vertically rigid pinned support (view from top).

Table 1
Mixture proportions of the studied concrete.

	Quantity (kg/m^3)
Cement type I 42.5 R	419.8
Mineral addition (calcareous filler)	179.3
Superplasticizer	6.7
Sand 1 (fine)	416.2
Sand 2 (coarse)	315.3
Gravel	848.5
Water	174.5

4096 points (40.96 s), which resulted in a frequency resolution of 0.024 Hz.

As the final goal is to track the evolution of *f*, the calculated spectra associated with different time instants were organized in a way that permits the rapid observation of the frequency content evolution. For that purpose, a colour map that consists of a joint view of all the spectra placed side by side was used (Fig. 5 —the greyscale intensity is a function of the amplitude). In this map the evolution of the natural frequencies is represented by continuous lines formed by points with higher amplitude (dark ascending and continuous line).

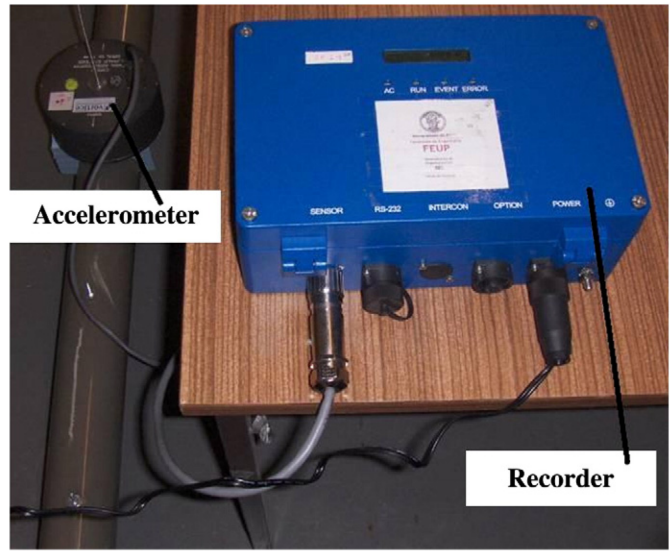

Fig. 4. Accelerometer and recorder used in the experiment.

4. Results: concrete stiffness evolution

4.1. Period 0–14.9 days (flexible supports)

Results obtained for the period starting just after concrete casting and extending until the age of 14.9 days were divided in two parts: an initial one pertaining to the first 72 h of monitoring, and a second related to the remaining period. The colour map regarding the spectra of frequencies for the composite beam until the age of 72 h is depicted in Fig. 5: as far as the first vibration mode is concerned, it can be observed that the initial value of *f* is of circa 7.8 Hz until the age of ~3 h, instant after which a very steep frequency ascending branch occurs, rapidly reaching 23.3 Hz at the age of 14 h. After this strong evolution the increase in *f* occurs very slowly, reaching 25.5 Hz at 72 h and 26.1 Hz at 357 h (see Fig. 6). As the ambient excitation cannot be classified as a white noise (which would require equal energetic participation of all frequencies of the excitation spectrum), beyond *f* and the natural frequencies of higher order modes of the composite beam, some further frequencies are identified in Fig. 6 – for instance 18.6 Hz, 32 Hz and 38 Hz –, as expressed by the extra horizontal lines (dashed or continuous). These lines are related to the frequency content of machines working in the neighbouring laboratory areas, namely the device used in the climatic chamber to control the environmental temperature and relative humidity. However, and as far as identification of the first beam resonant frequency *f* is concerned, this is not a real problem, as it is actually quite well defined in both Figs. 5 and 6.

4.2. Period 14.9–15.08 days (rigid simple supports)

As mentioned in Section 2, at the age of 357 h (14.9 days) the support conditions for the composite beam were changed, eliminating the 'small cantilevers' associated to the flexible rods, and switching to an arrangement where the pinned supports performed as infinitely rigid along the vertical direction (rigid simple supports — see Fig. 3). Henceforward ambient vibration tests were pursued by recording one time series of 15 min per hour, resulting in the frequency power spectra reproduced in Fig. 7: in the three presented spectra a maximum occurs at 38.3 Hz, being therefore this value associated with the natural frequency of the beam with the rigid supports, rather different from the value of 26.1 Hz measured 1 h before the change of support conditions (from flexible to rigid). Given the fact that during this period hardening of concrete is almost negligible, this rise in *f* should be related only to the added stiffness of the whole system, caused by elimination of the 'small cantilever' rods flexibility. For this reason, determination of concrete E-modulus during the first 357 h will have to explicitly reproduce those supporting rods on the structural system for the composite beam.

4.3. Ambient vibration and static test at the age of 28 days (rigid simple supports)

Ambient vibration tests with one 15 min time series were performed just before the static loading experiment, and with nine 15 min time series distributed in 9 h after it. As it can be seen in Fig. 8, before the static test and at the age of 28 days *f* was 38.4 Hz, which is rather similar to what was recorded at the age of 15 days (see previous section), revealing that the composite beam stiffness evolved

Table 2
Properties of the acrylic.

	Value
E-modulus	3.3 GPa
Poisson's coefficient	0.39
Density	1190 kg/m^3
Thermal conductivity	0.19 W/mK
Specific heat	1.47 J/gK

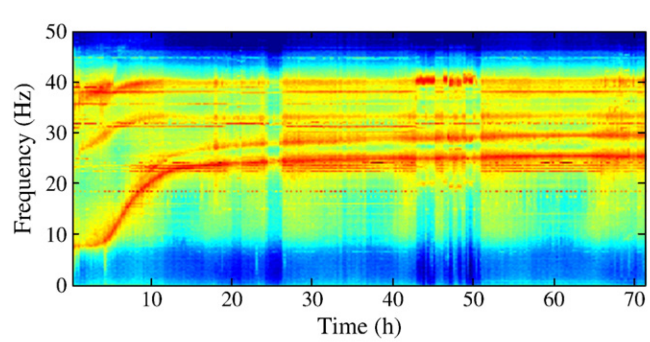

Fig. 5. Measured frequencies during the first 72 h (flexible supports).

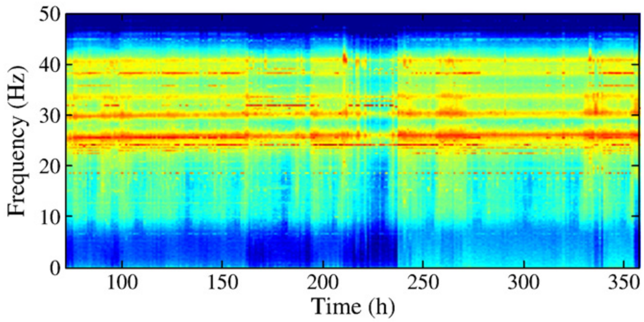

Fig. 6. Measured frequencies between 72 h and 357 h (flexible supports).

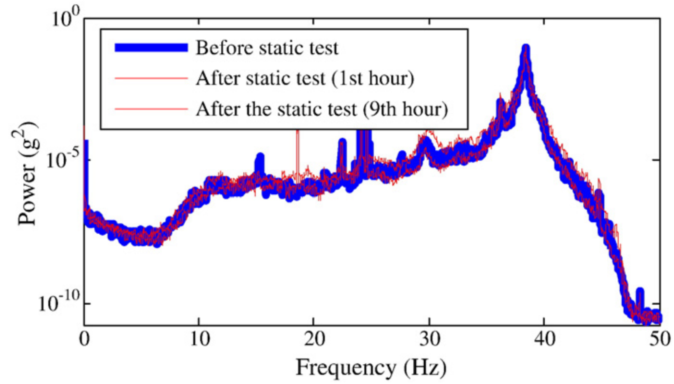

Fig. 8. Power spectra before and after the static test.

negligibly along the interval of 15–28 days. Also, f kept constant after the static loading test, indicating that no cracking was induced to the concrete.

The composite beam with rigid simple supports was statically loaded by using a succession of masses with 5 kg each, applied on top of the accelerometer located at mid-span, ensuring concrete tensile stresses to remain well below the tensile strength, and that linear elastic behaviour would be observed everywhere in concrete. Deflections at mid-span were measured using two LVDTs, placed at the lower face of the composite beam. These mid-span deflections, along with the applied masses, are depicted in Fig. 9: it can be observed that proportionality exists between the accumulated mass and the corresponding deflection, and that both LVDTs yield quite similar results. Also, some creep effects during the small periods of load application can be seen, which is particularly evident after the final unloading of the beam, when a residual deformation vanishing along time is discernible.

As the purpose of this static loading test was to obtain a reference value for the E-modulus of concrete, in Fig. 10 the mid-span deflections observed per each kilogram of applied mass are plotted for each of the 18 loading/unloading events reproduced in Fig. 9.

4.4. Concrete E-modulus measured from compressive tests

Evolution of concrete E-modulus obtained in compressive tests performed in cylinders cast with the same concrete batch used for the composite beam are reproduced in Table 3. It becomes evident that concrete E-modulus evolves from an average value of 27.7 GPa at the age of 19 h, up to 33.4 GPa at the age of 28 days, showing that the fastest evolution takes place within the first 19 h.

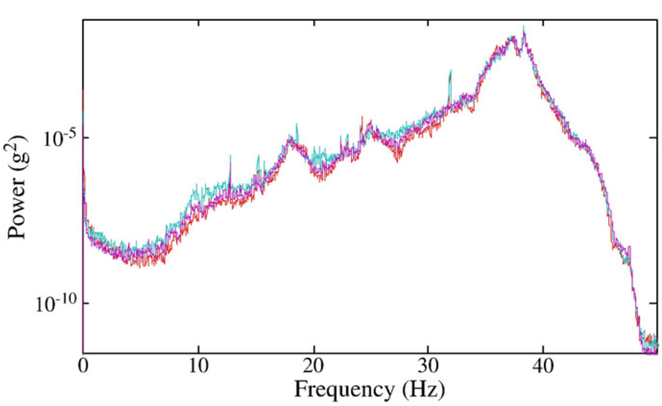

Fig. 7. Power spectra in the period 358 h–362 h (rigid supports).

5. Identification of concrete E-modulus and discussion of results

5.1. Concrete E-modulus at the age of 28 days

The experiments performed allow to determine concrete E-modulus at the age of 28 days by three dissimilar methods: ambient vibration and static loading (with the composite beam), and compressive testing (with cylinders). According to Table 3, the latter method provided an average value for the concrete E-modulus of about 33.4 GPa.

Regarding the static loading test in the composite beam, and bearing in mind the results plotted in Fig. 10, the average mid-span vertical deflection per unit of applied mass is 0.0098 mm/kg. With due account to standard elastic formulae expressing the mid-span deflection on a simply supported composite beam due to a concentrated load, one gets a E-modulus for concrete at the age of 28 days equal to 33.3 GPa, quite consistent with the value provided by the compressive testing of cylinders.

Concerning the results obtained with ambient vibration tests at the age of 28 days, which led to a resonant frequency of 38.4 Hz for the composite beam, an analytical formulation relating f with the concrete E-modulus will be presented. Taking advantage of the symmetry of the beam, the considered geometry is depicted in Fig. 11. In this figure $\phi(x)$ is the vertical deflection mode, x denotes the abscise along the beam axis, $\overline{m}$ is a uniformly distributed mass, m_p is a mass concentrated at mid-span, k is a spring constant (related to the vertical stiffness of the 'small cantilevers' at each support), L is half of the span and $\overline{EI}$ is the distributed flexural stiffness of the composite beam.

Given the high slenderness of the beam, relevance of shear to its mid-span vertical deflection is negligible, and therefore it will be disregarded for simplicity. So, along time t the free vibration equation for the composite beam is [31]

$$\overline{EI}\frac{\partial^4[\phi(x)Y(t)]}{\partial x^4} + \overline{m}\frac{\partial^2[\phi(x)Y(t)]}{\partial t^2} = 0 \qquad (1)$$

where $Y(t)$ represents the amplitude of the vertical displacement, expressed in relation to the deflection mode $\phi(x)$. After some mathematical manipulation of Eq. (1) [31] it is possible to express $\phi(x)$ as a function of four real constants A_1, A_2, A_3 and A_4, in the form,

$$\phi(x) = A_1\cos(ax) + A_2\sin(ax) + A_3\cosh(ax) + A_4\sinh(ax), \qquad (2)$$

$$with\ a = \sqrt[4]{\frac{w^2\overline{m}}{\overline{EI}}}$$

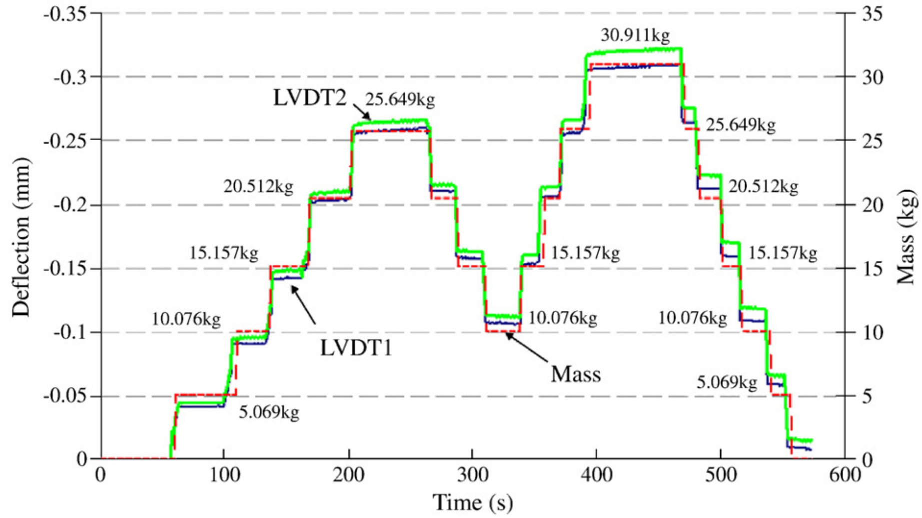

Fig. 9. Mid-span masses and deflections during the static test.

where $w = 2\pi f$. At this stage boundary conditions need to be applied to Eq. (2): for the present beam, with a vertical spring on the left and a vertical sliding support on the right, one has:

$$\text{At } x = 0: \quad \overline{EI}\phi''(0) = 0 \qquad \overline{EI}\phi'''(0) = -k\phi(0) \tag{3}$$
$$\text{At } x = L: \quad \overline{EI}\phi'''(L) = -w^2\phi(L)m_1 \qquad \phi'(L) = 0$$

(symbol (.)′ means derivative of (.)). Introducing these boundary conditions in Eq. (2) a set of equations is obtained, whose eigenvalues w may be computed according to:

$$-1/(2k)\begin{bmatrix} \overline{EI}a^3\sin(aL)^2w^2m_p + 2\cosh(aL)kw^2m_p\sin(aL) \\ +\cosh(aL)^2w^2m_p\,\overline{EI}a^3 + 2\left(\overline{EI}\right)^2a^6\sin(aL)\cosh(aL) \\ -\overline{EI}a^3\sinh(aL)^2w^2m_p + 2\cos(aL)\left(\overline{EI}\right)^2a^6\sinh(aL) \\ -4\cos(aL)k\,\overline{EI}a^3\cosh(aL) + \cos(aL)^2w^2m_p\,\overline{EI}a^3 \\ +2\cos(aL)w^2m_p\,\overline{EI}a^3\cosh(aL) \\ -2\cos(aL)kw^2m_p\sinh(aL) \end{bmatrix} = 0 \tag{4}$$

Bearing in mind that at the age of 28 days the composite beam is sustained by vertically rigid pinned supports, k turns infinite then after. Furthermore, for the setup considered one has: $L = 0.9$ m, $\overline{m} = 17.0176$ kg/m (calculated based on the geometry of the acrylic tube and on the densities of the materials involved, which are 2344 kg/m^3 for the concrete and 1190 kg/m^3 for the acrylic) and $m_p = 1.135$ kg (half of the accelerometer's mass). Note that $\overline{m}$ is constant throughout the experiment, as the acrylic formwork fully seals the concrete. Regarding the value of $\overline{EI}$, it may be expressed based on the values E_aI_a and EI referring to the acrylic cylinder and to the concrete, respectively:

$$\overline{EI} = E_aI_a + EI = 3.3\times10^9\frac{\pi\left(0.1^4-0.092^4\right)}{64} + E\frac{\pi\,0.092^4}{64}\left[\text{in N m}^2\right] \tag{5}$$

Introducing all these data in Eq. (4), and having in mind the measured frequency $f = 38.4$ Hz that leads to $w = 241.3$ rad/s, the concrete E-modulus at the age of 28 days is computed as $E = 33.6$ GPa, remarkably coherent with the values of 33.4 GPa and 33.3 GPa obtained with the previously mentioned methods. This coherence led to a great confidence in the results obtained with the performed ambient vibration tests for the age of 28 days.

5.2. Concrete E-modulus evolution during the period 0–14.9 days

The analytical model of the beam was used together with the frequency of 38.3 Hz identified from the ambient vibration test conducted at the age of 15 days (358 h–362 h). The corresponding calculated concrete E-modulus is 33.4 GPa, almost the same as the one for the age of 28 days (33.6 GPa). This value was not confirmed in the

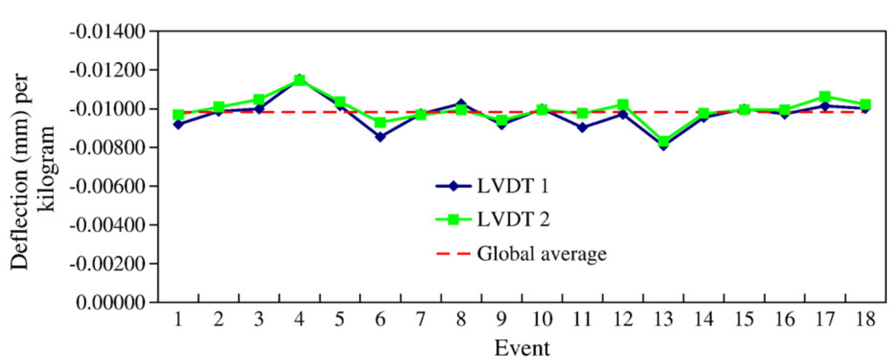

Fig. 10. Deflections per kg of applied mass during the static test events.

Table 3
Evolution of E-modulus in compressive tests of cylinders.

Age	E-modulus (GPa) 3 specimens	Average E-modulus (GPa)
19 h	29.0, 26.7, 27.4	27.7
24 h	26.8, 27.5, 27.0	27.1
2 days	29.1, 27.8, 28.3	28.4
3 days	29.7, 28.5, 26.8	28.3
7 days	30.5, 31.7, 30.9	31.0
28 days	33.4, 33.6, 33.1	33.4

compressive tests performed, but the very similar concrete E-modulus obtained for the ages of 15 and 28 days are quite consistent with usual observations in this concrete property.

As mentioned previously, a drastic change in the resonant frequency was identified with the ambient vibration technique when at the age of 14.9 days the vertical supports of the composite beam were changed from flexible ($f=26.1$ Hz) to infinitely rigid ($f=38.3$ Hz). Since concrete E-modulus at this age has just been identified to be 33.4 GPa, it is possible to adequately fit the value of k in the analytical model to correctly reproduce the supporting conditions during the period 0–14.9 days (whilst flexible 'small cantilevers' apply). Furthermore, instead of being really centred with the supporting flanges (Fig. 12a), during the experiment it was detected that the beam was laterally deviated 4 mm towards one flange (in both extremities), as reproduced in Fig. 12b. Based on the resulting 'small cantilever' spans of 23 mm and 31 mm, the estimated spring constant k for the analytical model would be:

$$k = \frac{3 \times 180 \times 10^{9} \pi\, 0.004^{4}}{64}\left(\frac{1}{0.023^{3}} + \frac{1}{0.031^{3}}\right) = 785507\ \mathrm{N\,m^{-1}} \tag{6}$$

By using this spring constant together with $E=33.4$ GPa, the predictable frequency using Eq. (4) would be 26.37 Hz (at the age of 14.9 days), which is quite similar to the 26.1 Hz obtained from the ambient vibration modal identification. To achieve a perfect match a slight correction to the estimated spring constant k was further introduced, thus finally resulting $k=756600\ \mathrm{N\,m^{-1}}$.

At this stage, the analytical model together with the adopted parameters is considered valid for the initial period of monitoring. With the experimental data collected via the ambient vibration tests, it is then possible to relate the identified f for the composite beam with the concrete E-modulus, and thus draw its evolution along time since the instant of casting. The procedure for relating f with E is the same as described for the age of 28 days: *(i)* using the ambient vibration test $w=2\pi f$ is identified; *(ii)* Eq. (4) is used to obtain $\overline{EI}$ and *(iii)* finally E is calculated from Eq. (5).

The evolution of concrete E-modulus identified according to this methodology, together with the one obtained from the compressive tests performed on concrete cylinders, are plotted in Fig. 13 and in Fig. 14. Coherence between the ambient vibration predictions and the results from compressive testing on cylinders is quite satisfactory, particularly for the ages of 2, 3, 7 and 28 days. However, for the ages of 0.8 days and 1 day the ambient vibration test identifies lower values for the concrete E-modulus. But here the reader should be aware that specimens with different sizes and curing conditions are being used: the ambient vibration test pertains to a concrete specimen that is a cylinder with a diameter of 92 mm, cured inside a 4 mm thick acrylic formwork, whereas compressive E-modulus testing regards to greater diameter cylindrical specimens (150 mm), cured inside a 26 mm thick plastic formwork. Therefore, these differences in size and boundary conditions led for more heat development to occur in the compressive cylinders than in the composite beam, and thus to a faster development of the material microstructure, which is more evident at the first hours and fades as concrete ages.

Still regarding to Fig. 13, it is noteworthy to mention the clear ability of the ambient vibration test to identify the instant at which structural setting occurs, and concrete stiffness starts developing at a fast rate: at the age of about 3.6 h, for the present application. This structural setting time, as well as the early evolution of material stiffness, are known as being rather important to actually determine when concrete starts to hold stresses, and the subsequent stress development, which is of paramount importance for numerical simulation of concrete structures at early ages [32,33].

6. Additional set of experiments with the final recommended setup (rigid simple supports)

The experiments reported in Sections 2–5 provided interesting results in regards to the capabilities of the proposed experimental technique to continuously measure E-modulus of concrete since casting. However, the support conditions of the beam have been changed during the measuring period, and the repeatability of the method has not been evaluated. Bearing these issues in mind, it was decided to cast two further beams. The adopted experimental setup was basically the same as described in Section 2, with the exception that vertically rigid pinned supports, as depicted in Fig. 3, were adopted for the beam throughout the whole experiment. These are, in fact, the support conditions recommended for the setup to be adopted in further experiments with the novel method proposed for measurement of concrete E-modulus evolution.

The beams under test are identified as Beam 1 and Beam 2, with Beam 1 having the same acrylic formwork as described in Section 2. Even though both beams were purchased as similar, it was observed that Beam 2 had a slightly different cross section than Beam 1, with an internal diameter of 91 mm (instead of 92 mm). The concrete used for casting these two beams had the following mix proportions: cement type I 42.5 R — 407.2 kg/m^3; mineral addition (calcareous filler) — 186.1 kg/m^3; superplasticizer — 11.34 kg/m^3; sand 1 (fine) — 422.4 kg/m^3; sand 2 (coarse) — 327.2 kg/m^3; gravel — 823.3 kg/m^3 and water — 152.1 kg/m^3. The resulting concrete density was measured on hardened specimens, and the value of 2340 kg/m^3 was obtained.

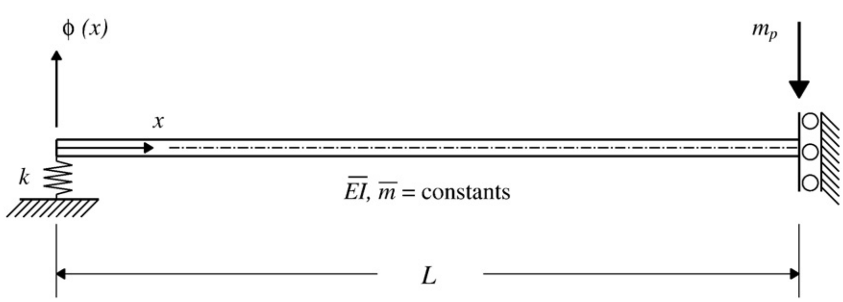

Fig. 11. Scheme of half of the composite beam.

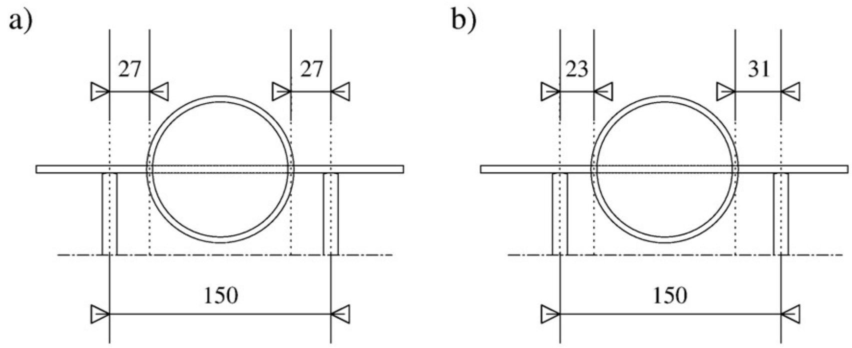

Fig. 12. Beam cross-section at the supports: a) original plan; b) actual placement.

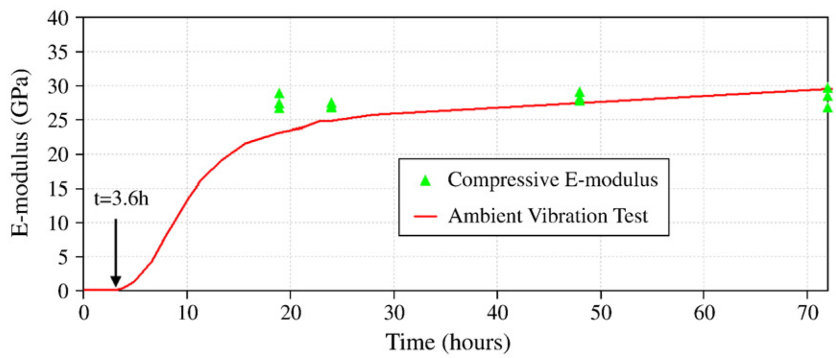

Fig. 13. Evolution of concrete E-modulus until 72 h.

The measured power spectra for both beams during the first 24 h after casting are depicted in Fig. 15. Due to the differences on the internal diameters of these beams, thus conducting to different masses and stiffnesses, the expectable resonant frequencies should not be exactly the same. Nonetheless, the resemblances of the power spectra are striking, as it can be confirmed in Fig. 16a, where the evolution of the first frequency of both beams is represented during the first 24 h, and in Fig. 16b, where the evolution is shown for the total period of study (28 days). With these identified frequencies and the following data:

- Beam 1: Acrylic internal diameter = 92 mm; Acrylic external diameter = 100 mm; $L = 0.9$ m; $\overline{m} = 17.0176$ kg/m; $m_p = 1.400$ kg and $k = \infty$;
- Beam 2: Acrylic internal diameter = 91 mm; Acrylic external diameter = 100 mm; $L = 0.9$ m; $\overline{m} = 16.852$ kg/m; $m_p = 1.400$ kg and $k = \infty$;

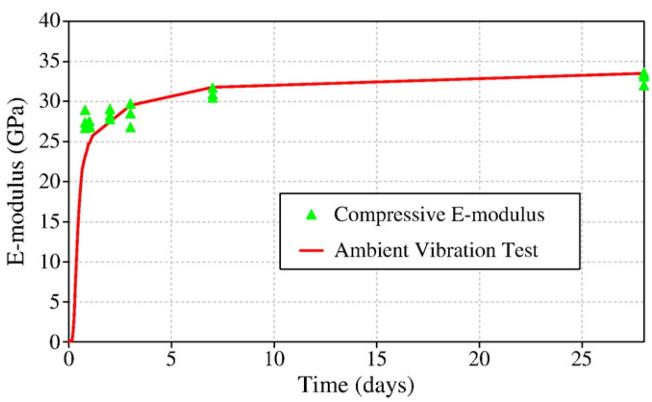

Fig. 14. Evolution of concrete E-modulus until 28 days.

the concrete E-modulus evolution curve for each beam was calculated, being reproduced in Fig. 17 for the periods of 0–24 h and 0–28 days. It can be confirmed that curves concerning both beams are almost coincident, which emphasises the robustness and repeatability of the proposed method for identification of concrete E-modulus evolution since casting.

Concrete E-modulus was measured at the age of 28 days through compressive tests of standard cylinders cast with the same batch, which rendered an average value of 41.6 GPa. A static loading test similar to the one described in Section 4.3 was also conducted at the age of 28 days, and the obtained concrete E-modulus was 40.9 GPa. Resemblance of these E-modulus values with the ones reproduced in Fig. 17 for the age of 28 days in Beam 1 (40.1 GPa) and in Beam 2 (40.8 GPa) highlights, once more, the adequacy of the novel method proposed to identify the E-modulus of concrete.

7. Conclusions

The present paper detailed a pilot project for monitoring the E-modulus evolution of concrete since casting, which is based on the non-destructive technique of ambient vibration testing, and on the continuous identification of the frequency of vibration of the first flexural mode of a simply supported acrylic–concrete beam. In parallel to this, complementary tests were conducted, comprising standard compressive E-modulus characterization in concrete cylinders of the same batch, as well as static loading of the composite beam. The outcome of the several conducted experiments led to the conclusion that the proposed experimental methodology is quite robust, and leads to quite satisfactory and promising results, provided that the

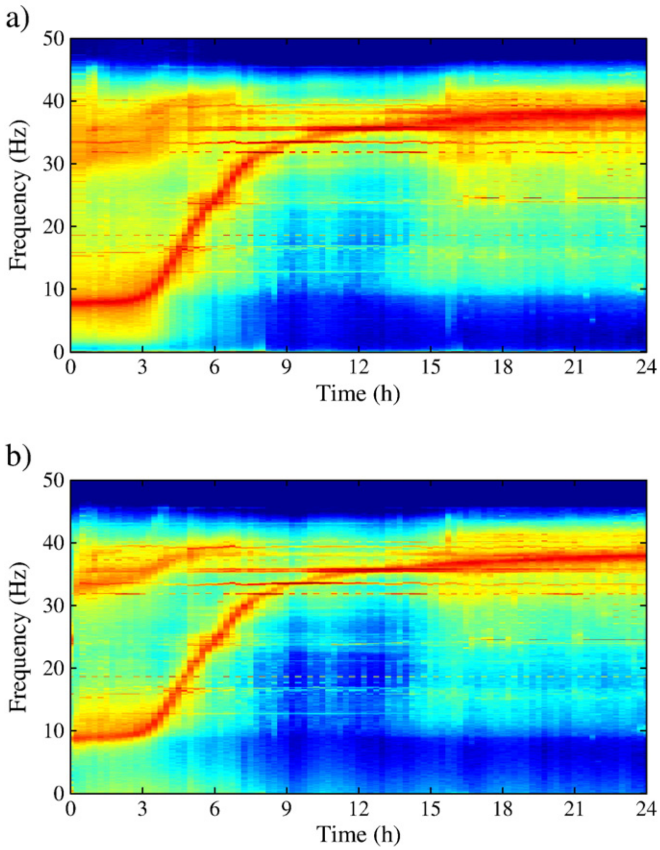

Fig. 15. Power spectra during the first 24 h for: a) Beam 1; b) Beam 2.

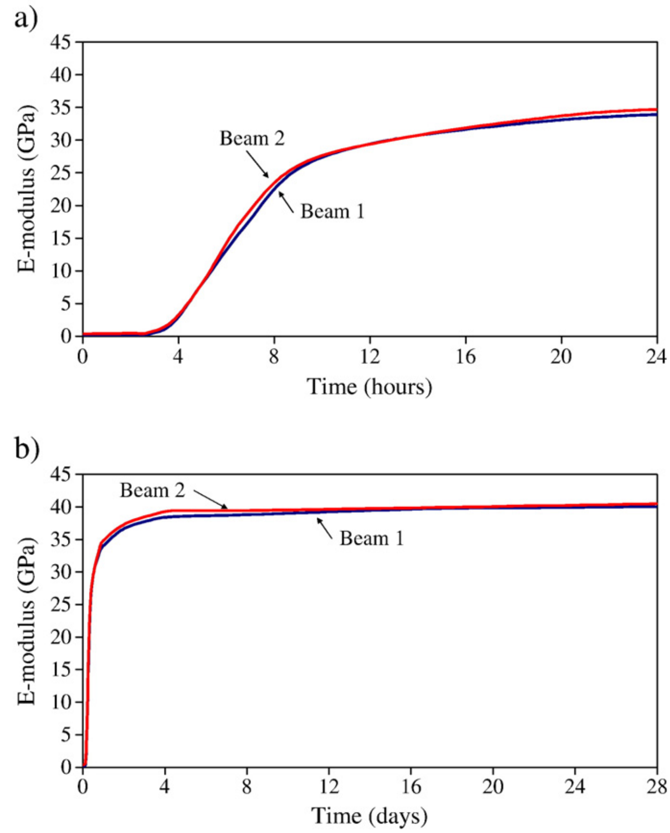

Fig. 17. Evolution of computed E-modulus for Beams 1 and 2 for the periods: a) 0–24 h; b) 0–28 days.

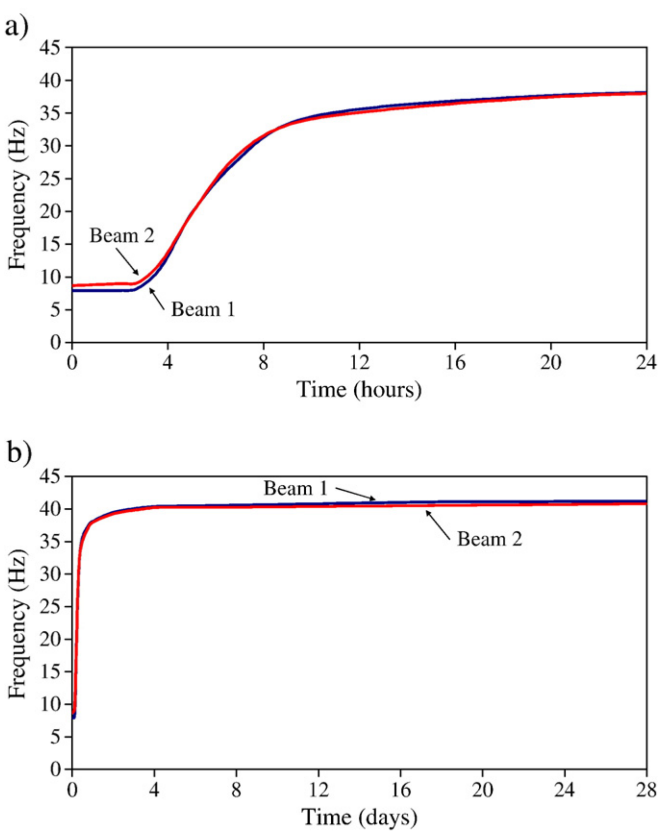

Fig. 16. Evolution of resonant frequencies for Beams 1 and 2 for the periods: a) 0–24 h; b) 0–28 days.

supporting conditions of the composite beam are well defined. In this concern, vertically rigid pinned supports were found to be the most adequate for the experimental setup.

In order to assess the repeatability of the methodology, further tests were conducted in two additional beams. The good coherence of the obtained concrete E-modulus in both beams pointed once more to the reliability of the proposed method.

This experimental technique reveals itself as being an alternative to currently existing non-destructive techniques for E-modulus evaluation (ultrasound or resonant frequency methods), since it allows measurement of the first bending frequency of vibration of the composite beam, which is directly related to the E-modulus of concrete. The proposed method provides a continuous monitoring without necessity of specific excitation supply, as ambient vibration suffices. It allows measurement of concrete E-modulus since casting (less than 15 min occur since the end of casting operations and the beginning of actual measurements), providing valuable information about the structural setting time, as well as clear information about the evolution of E-modulus while concrete is not 'de-mouldable', where classical resonant methods fail.

Hence, this experimental technique has a considerable potential to obtain relevant parameters for numerical modelling of early age concrete structures, as well as to characterize the performance of concrete mixes with regards to inclusion of additions, partial substitutions, new materials and others.

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