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Evaluation of the elastic modulus of concrete using non-destructive ultrasonic methods and the natural vibration method

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ABSTRACT
The compressive strength of concrete is one of the main indicators of structural safety, quality, and durability. However, for designers, the modulus of elasticity is equally essential during the structural modelling phase, as it directly influences the behaviour of the material under load. In this study, the dynamic modulus of elasticity was obtained and evaluated by means of the ultrasound method, and compared with the results obtained by the excitation method using the Sonelastic® system. A set of 48 cylindrical concrete samples with different strengths was used, allowing comparisons between the acoustic methods in different strength classes. The data were essential to validate the dynamic modulus estimates and verify their compatibility with the normative values. Based on these parameters, measurements were monitored at 14 and 28 days, the latter being considered as a reference. The measurements facilitated comparisons between the acoustic methods selected for estimating the dynamic modulus of elasticity, as well as comparisons with the static modulus of elasticity results established by the ABNT NBR 6118:2023 standard. The evaluation of metrological performance was carried out using standardized errors, which verified the compatibility of the results obtained with the normative methods.

Section: RESEARCH PAPER

Keywords: dynamic modulus of elasticity; ultrasonic testing in concrete; natural vibration method

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1. INTRODUCTION

The modulus of elasticity is an essential property for characterizing the stress of materials, relating the applied stress to the resulting deformation, and it is widely used in civil engineering [1]. Traditionally, its determination is made through destructive tests known as Eci (initial tangent modulus of elasticity) and Ecs (secant modulus of elasticity), which are based on empirical equations, such as those demonstrated in NBR 6118:2023 [2]. However, this standard preferentially recommends the experimental granting of the parameter according to the procedures of ABNT NBR 8522:2021 [3].

Despite being well-established, destructive tests compromise the integrity of the samples, making subsequent reassessments unfeasible [1]. As an alternative, non-destructive testing (NDT) methods are gaining prominence because they allow the assessment of mechanical properties without damaging the material, which favours its monitoring over time [4].

In this study, two standardized NDT techniques were applied to estimate the dynamic modulus of elasticity of concrete: the method of natural vibration frequencies, according to ABNT NBR 8522-2:2021, and the ultrasonic test, according to ABNT NBR 8802:2019 [3], [5]. Both approaches are based on the propagation of high-frequency acoustic waves (above 20 kHz), offering reliable results that are sensitive to internal variations in the material [6]. The ultrasonic method, in particular, stands out for allowing the detection of discontinuities, such as cracks and voids [7]. The integration of different non-destructive techniques represents a significant advance in the mechanical characterization of materials, contributing to more sustainable and efficient practices in engineering [7].

In view of this, the present work aims to analyse two non-destructive methodologies applied to the estimation of the modulus of elasticity in concrete samples, based on the propagation of acoustic waves.

2. THEORETICAL FRAMEWORK

The modulus of elasticity of concrete can be determined by static or dynamic methods, which produce different values depending on the nature of the stress applied [4]. The static modulus is obtained by means of traditional mechanical tests, such as axial compression, in which permanent deformations occur and non-linear effects of the material are considered [4]. On the other hand, the dynamic modulus is estimated based on the propagation of acoustic waves or the vibration frequency, reflecting the elastic behaviour of the material under excitation, without causing damage to the sample being tested [4].

Several studies in the technical literature have explored the relationship between the propagation of ultrasonic pulses in concrete and its mechanical properties, especially the strength and resistance of the material [6], [8]. In this context, NDT tests are consolidated as valuable tools for the characterization of concrete, allowing in situ evaluations, with the possibility of reproducing the tests in the same regions, without compromising the integrity of the material [6]. This characteristic is particularly relevant in structures that interrupt continuous monitoring, contributing to the preservation and longevity of buildings [7].

In this work, two renowned acoustic techniques are explored for the estimation of the dynamic modulus of elasticity of concrete, considering different curing ages (14 and 28 days). The first approach is the direct transmission ultrasonic test, which uses two transducers positioned on opposite sides of the sample, allowing the longitudinal propagation of acoustic waves [9]. The second technique demonstrated is the method of natural vibration frequencies, which consists of the mechanical analysis of the test specimen through a controlled impact, usually with a metal hammer. The vibrational response caused is captured by an acoustic sensor, transformed into an electrical signal, and processed by specific software, which determines the value of the sound functionality module based on the fundamental vibration frequency [4], [9].

Both techniques are based on the propagation of mechanical waves inside the concrete, but they have different natures: while the ultrasonic test evaluates the speed of longitudinal waves, the vibration method focuses on the response of the test specimen to dynamic movement [10]. These approaches were chosen to compare their applicability and sensitivity in estimating the dynamic modulus at different curing ages, contributing to the advancement of non-destructive characterization methodologies in concrete samples.

2.1. Ultrasound method (E_{cd})

In the propagation method, an ultrasonic pulse is emitted by a transducer coupled to the surface of the material, in this case, concrete. This arrangement, known as direct transmission, is widely used in tests applied to concrete elements, and it was adopted in this study. By measuring the transit time between the emitted signal and the one received by the opposite transducer, it is possible to determine the propagation speed of the ultrasonic waves in the material [7]. With this data, the dynamic modulus of elasticity (GPa) can be calculated based on the direct relationship between the wave speed and the physical properties of the material, as shown in equation (1), [4]:

$$v = \frac{l}{t}, \tag{1}$$

where v is the pulse velocity (mm/µs), and l is the distance (mm) travelled by the ultrasonic wave in the longitudinal direction between the emitting and receiving transducers, during a previously evaluated time interval t (µs). Then, with the velocity value, it is possible to estimate the dynamic modulus of elasticity (E_{cd}) [3], as shown in equation (2):

$$E_{\mathrm{cd}} = v^2 \cdot \rho \cdot \frac{(1+\mu)\cdot(1-2\,\mu)}{1-\;\mu}, \tag{2}$$

where: v is the pulse velocity (m/s) calculated in (1), ρ is the specific mass of concrete (kg/m³), and μ is the Poisson's ratio, where a common value used is 0.20.

2.2. Natural vibration method (E_{cd})

The natural vibration method (GPa) follows the guidelines of ASTM E1876-09 [10] and ABNT NBR 8522-2:2021 [3]. This method is based on determining the fundamental flexural resonance frequency (F_{f}), obtained by impulse conduction, generally applied with an impact hammer. The signal capture and the analysis are performed with the aid of Sonelastic® software, which processes the vibrational response of the test specimen, as illustrated in Figure 1.

Initially, the samples are weighed, and the boundary conditions are applied to the test specimen, which involves marking specific points at each of its ends, as illustrated in Figure 2. Subsequently, the effective length (c) is calculated using equation (3), [3]:

$$c = \;0{,}224 \cdot h\,, \tag{3}$$

where c is the length (mm), 0.224 is a constant established by the program based on boundary conditions set by the program itself, and h is the height of the test specimen (mm).

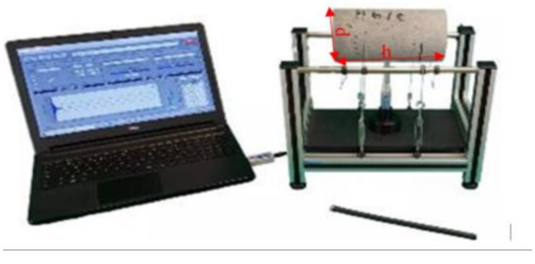

Figure 1. Sonelastic® System Apparatus.

Figure 2. Demonstration of how to mark the test specimens.

Using equation (4), the value of the modulus of elasticity can be obtained for each sample tested [8]:

$$E_{\mathrm{cd}} = 1.6067 \cdot \frac{L^3}{D^4} \cdot m \cdot F_{\mathrm{f}}^2 \cdot T1\,, \tag{4}$$

where E_{cd} is Young's dynamic modulus, m is the mass of the cylinder, D is the cylinder diameter (mm); L is the length of the cylinder (mm), F_{f} is the fundamental resonance frequency of the cylinder in bending (calculated automatically by the system), and $T1$ is the correction factor applied by the system, which considers the finite thickness of the cylinder.

2.3. NBR 6118 method (E_{ci}) and (E_{cs})

To determine the values of the static modulus of elasticity (GPa), it is necessary to use normative equations, such as (5) and (6) [2]:

$$E_{\mathrm{ci}} = \alpha E \cdot 5600\,\sqrt{f_{\mathrm{ck}}}, f_{\mathrm{ck}} \leq 50\ \mathrm{MPa}\,, \tag{5}$$

where αE is the modulus of elasticity of gravel and f_{ck} is the characteristic tensile strength of concrete.

$$E_{\mathrm{cs}} = \alpha i \cdot E_{\mathrm{ci}}\,, \tag{6}$$

where $\alpha i = 0.8 + 0.2 \cdot \frac{f_{\mathrm{ck}}}{80} \leq 1.0$ and E_{ci} is the value obtained by (5).

However, the standard itself [9] highlights that this approach must be applied in situations where performing the dynamic test is not feasible [2].

2.4. Evaluation of measurement uncertainties

The measurement uncertainties in this research were assessed according to the ISO GUM guidelines (Evaluation of measurement data — Guide to the expression of uncertainty in measurement), which establishes that any measurement result can only be considered complete if accompanied by the associated uncertainty [9]. Uncertainty is a fundamental parameter for determining the quality of measurements and assessing their proximity to the expected value [11]. Thus, measurements with greater uncertainty have less credibility, while those with lower uncertainty are considered more reliable [11].

Type A and B uncertainties were considered in estimating the total uncertainty of the results. Type A uncertainty was obtained from the standard deviation of repeated measurements, reflecting experimental variability. Type B uncertainty refers to the equipment resolution (0.01 GPa), assumed to have a rectangular distribution, divided by $\sqrt{12}$, resulting in approximately 0.00289 GPa. The final uncertainty used is the combined uncertainty, which is calculated by the square root of the sum of the squares of the type A and B components, as recommended by the ISO GUM [11].

2.5. Normalized error

According to the ISO/IEC GUIDE 17043:2023, the normalized error is a dimensionless measure used in metrology to assess the performance of a measuring instrument or the compatibility of declared results. This method ensures that the evaluations of concrete properties over time are accurate and compatible within the declared uncertainties [12].

To compare measurement data between different methods, the normalized error (E_{n}) statistical approach was employed to verify the data sets (the actual measurement and its associated uncertainty). Equation (7) is used to calculate the normalized error [12].

$$E_{\mathrm{n}} = \frac{x1 - x}{\sqrt{U_{x1}^2 + U_x^2}}\,, \tag{7}$$

where E_{n} is the normalized error, $x1$ is one method and x is the other method to be compared, while U_{x1} and U_x are their respective expanded uncertainties.

For the analysis of the results, if the absolute amount of the value of E_{n} is less than 1, the compared values are considered statistically equal. Otherwise, the values are considered statistically different.

Regarding the originality of this work, its main contribution lies in the metrological approach applied to the comparative analysis of non-destructive methods, something that has not been explored in previous studies. Although the combination of acoustic emission and ultrasound techniques has been mentioned in the literature, this work stands out by comparing methods based on static and dynamic tests, focusing on the statistical evaluation of normalized errors between the methods. Thus, the proposal not only uses already known methods, but also innovates by addressing their applicability from a quantitative, metrological, and normative perspective, providing more robust results for technical decision-making.

3. MATERIALS AND METHODS

This section presents the materials and experimental procedures used in the preparation, moulding, and testing of the concrete specimens.

3.1. Sample preparation

The specimens were prepared in cylindrical metal moulds with a diameter of 10 cm and a height of 20 cm. The mixes consisted of types 0 and 1 crushed stone, water, type III Portland cement (CPIII), sand, and approximately 0.5 % of the superplasticiser additive Tec-Flow 9030 in relation to the cement weight. It was observed that the superplasticiser improved the mixture's fluidity, facilitating the compaction and consolidation of the samples, as well as contributing to increased concrete strength. Four concrete mixes were produced, one for each reference compressive strength (f_{ck}): A (20 MPa), B (30 MPa), C (40 MPa), and D (50 MPa), totalling 48 specimens, with 12 for each reference f_{ck}, see Table 1.

After the concrete curing period, the samples underwent measurements of the following physical properties: diameter, height, density, and mass of each specimen. The dimensions were measured with a digital calliper, and the mass was measured using a Sartorius electronic balance model CP 4202 S, with a capacity of 4,200 g. All measurements were conducted in three consecutive repetitions for enhanced precision. Subsequently, the specimens were subjected to non-destructive testing to determine the dynamic modulus of elasticity, using ultrasonic and

Table 1. Composition of concrete mixtures estimated according to reference f_{ck}.

f_{ck} of reference	Cement kg	Water l	Sand kg	Stone kg	Additive ml
Mix A (20 MPa)	13.4	8.1	37.3	44.6	200.0
Mix B (30 MPa)	17.9	8.1	35.0	42.8	200.0
Mix C (40 MPa)	21.8	8.2	33.5	40.9	200.0
Mix D (50 MPa)	25.8	8.2	31.9	39.0	200.0

Figure 3. Measurement of the specimen to obtain the ultrasonic velocity.

impulse excitation techniques, as detailed in the following sections.

3.2. Ultrasonic contact method

An oscilloscope from the American company Agilent Technologies, with a resolution of up to 100 MHz, was used as shown in Figure 3, along with two 50 kHz ultrasonic pulse transducers (transmitter and receiver), model 58-E4800 from the Italian company Controls. The sensors were then coupled to the transducers using solid petroleum jelly from the Brazilian company Graxa Iguaçu.

In this method, the two transducers are positioned at each end of the sample, with one emitting an ultrasonic pulse, while the other receives it. Based on the pulse's return time and the speed of sound in the material, it is possible to calculate the Young's modulus using equation (5).

3.3. Impulse excitation method

Before starting the tests, it is necessary to weigh and measure the test specimens, as this information is essential for both carrying out the tests and performing subsequent calculations.

The 48 samples were prepared with boundary conditions as defined in equation (2), and then subjected to mechanical excitation using a metallic impact hammer, as illustrated in Figure 4.

3.4. Static modulus of elasticity E_{ci} and E_{cs}

In accordance with ABNT NBR 6118:2023, the E_c value was initially calculated for each concrete class using the corresponding f_{ck}. Subsequently, the E_{cs} values were determined based on the previously obtained E_{ci} values [2].

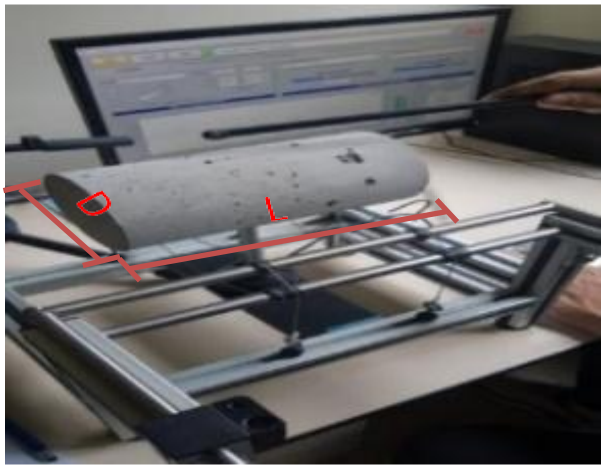

Figure 4. The test specimen positioned on the cables of the Sonelastic® system.

Table 2. Table with the results obtained by the ultrasonic method for 14 days and 28 days.

	14 Days		28 Days	
CP (f_{ck})	**E_{ci} (GPa)**	**U (GPa)**	**E_{cs} (GPa)**	**U (GPa)**
CP 20	32.28	0.58	35.46	0.61
CP 30	35.20	0.61	37.78	0.60
CP 40	37.85	0.82	39.84	0.80
CP 50	38.77	0.79	41.93	0.81

Table 3. Table with the results obtained by the natural vibrations method – Sonelastic® system for 14 and 28 days.

	14 Days		28 Days	
CP (f_{ck})	**E_{ci} (GPa)**	**U (GPa)**	**E_{cs} (GPa)**	**U (GPa)**
CP 20	25.37	0.51	27.90	0.77
CP 30	29.73	0.26	31.10	0.43
CP 40	35.69	0.42	36.81	0.62
CP 50	37.04	0.68	37.65	0.56

4. RESULTS

4.1. Ultrasonic method (E_{cd})

Table 2 summarises the results of the dynamic Young's modulus (ε) and the corresponding expanded uncertainty (U) for the ultrasonic testing.

The results of the ultrasonic method are shown in Table 2.

4.2. Natural vibrations method (E_{cd})

The results for the natural vibrations method are shown in Table 3.

Uncertainty is a fundamental criterion for establishing the quality with which these measurements are performed, and telling us how close they are to the expected value. Therefore, the greater the uncertainty, the lower the credibility of the results, and the lower the uncertainty, the higher their credibility. For both tests, the uncertainty values are quite low, representing between 2 % and 3 % of the estimated value for each of the methods, therefore, the values obtained are satisfactory [11].

Regarding the analysis of the evolution of Young's dynamic modulus from 14 to 28 days, it was clear that there was growth for the four mixtures, as shown in Figure 5.

4.3. Static modulus of elasticity – NBR 6118:2023 (E_c)

The results for the static modulus of elasticity – NBR 6118:2023 are shown in Table 4. Regarding the uncertainties associated with the values of the static elasticity modulus, it was observed that they were less than 2 %, which indicates that the results were also satisfactory.

4.4. Normalized error

Table 5 presents the values obtained with the different methods of determining the modulus of elasticity: M1,

Table 4. Table with the results obtained for static modulus of elasticity - NBR 6118:2023 (E_{ci} and E_{cs}) for 14 days and 28 days.

	14 Days		28 Days	
CP (f_{ck})	**E_{ci} (GPa)**	**U (GPa)**	**CP (f_{ck})**	**E_{ci} (GPa)**
CP 20	21.21	0.40	18.00	0.34
CP 30	25.51	0.98	22.30	0.85
CP 40	30.11	0.18	27.10	0.16
CP 50	34.45	1.04	31.86	0.96

Table 5. Normalized Error Values.

	M1-M2	M1-M3	M1-M4	M2-M3	M2-M4	M3-M4
CP 20	5.99	7.75	19.72	11.78	25.23	7.75
CP 30	2.46	5.22	10.69	9.17	14.80	9.09
CP 40	7.46	17.07	17.23	21.15	20.43	3.00
CP 50	1.83	2.72	3.92	5.22	5.40	2.53

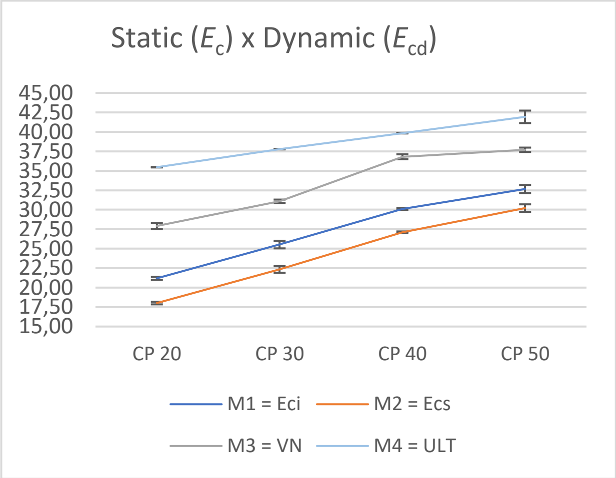

Figure 5. Graphical behaviour of the obtained E_c and E_{cd} values.

corresponding to the initial static modulus of elasticity (E_{ci}); M2, to the secant static modulus of elasticity (E_{cs}); M3, to the natural vibration method (VN); and M4, to the ultrasonic method (ULT). For all methods, a constant value of the Poisson modulus equal to 0.20 was adopted.

4.5. Comparative graph of E_c and E_{cd} values obtained (GPa)

For the static and dynamic elasticity modulus values obtained and compared with each other, see Figure 5.

The dynamic modulus of elasticity is generally 20 %, 30 %, and 40 % greater than the static modulus of elasticity for high ($f_{ck} \geq 40$ MPa), medium ($20 < f_{ck} < 40$ MPa), and low strength concretes ($f_{ck} \leq 20$ MPa), respectively [13].

As observed in other studies, the values of the dynamic modulus of elasticity (E_{cd}) were higher than the values of the static modulus of elasticity (E_c), as theoretically expected, since the sound tests are less influenced by factors such as microcracks, conventional and other energy dissipation mechanisms present in the material.

5. CONCLUSIONS

This study allowed monitoring the evolution of the dynamic (E_{cd}) and static (E_c) elasticity modulus at 14 and 28 days, according to the normative parameters, adopting the 28th day as a reference. The results revealed a behaviour consistent with that predicted in NBR 6118:2023, evidencing the progression of the modulus with the curing time.

The E_{cd} values were consistently higher than those of E_c, as already documented by Mehta and Monteiro (2014) [11], which validates the observed trend. The proportional age identified between the methods employed indicates not only compatibility between the techniques, but also robustness in the research carried out.

An analysis of the normalized errors (E_n) revealed that all values obtained between the compared methods were greater than 1. According to ISO/IEC 17043:2023, E_n values > 1 indicate that the methods present statistically significant differences compared to the reference values and are therefore not considered equivalent or comparable to each other. This means that, although all methods can be used individually to estimate the specification modulus, the results obtained by them should not be treated as equivalent.

The results obtained in this study indicated reliability and coherence with data from the technical literature, and reinforced its applicability in studies and practices of non-destructive characterization of concrete.

AUTHORS' CONTRIBUTION

Aline Marçal da Rocha: Designed the overall research structure and objectives. Wrote the manuscript and analysed preliminary results. Created tables and graphs to represent the data.

Tiago C. Dourado: Reviewed and edited, managed, and organized the datasets used in this study. Performed experiments, collected data, performed statistical analyses, and validated the results.

Sandro A. Miqueleti: Collected data, created tables, and organized data collection.

Rodrigo P. B. Costa-Felix: Supervised research activities and guided the team throughout the project. Coordinated tasks between authors and managed deadlines.

Robson Luis Gaiofatto: Assisted with research methodology and structuring.

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