Estimation of the dynamic modulus of elasticity of concrete using contact ultrasonic and impulse excitation methods.

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Abstract. It is extremely important to know the mechanical resistance to compression of concrete, precisely because it is related to the safety, quality, and durability of structures. However, when designers find themselves in a modeling stage of a structure, knowledge of the modulus of elasticity is essential. In practical terms, it is possible to estimate this property based on pre-established normative values. This practice, although avoiding costly experimental measurements, can lead to oversizing. For this research, this property was obtained and evaluated based on contact ultrasound tests and compared with the results obtained with the excitation method using the Sonelastic® system. To obtain the dynamic modulus of elasticity, the ultrasonic wave propagation test was used for concrete at 14 and 28 days with compressive strength selected to 20 MPa, 30 MPa, 40 MPa, and 50 MPa. All four mixes were made with the addition of a super plasticizer additive, which obtained the lowest water/cement ratio and dosages according to ABNT NBR 6118:2014 Concreto Armado - Procedimento. A set of 84 samples of cylindrical concrete specimens 100mm in diameter and 20mm in height were cast. The measurements allowed establishing comparisons among themselves between the selected acoustic methods for estimating the dynamic modulus of elasticity, as well as comparing with results of static modulus of elasticity established in ABNT NBR 6118:2014.

1. Introduction

The dynamic Young's modulus is a fundamental property of materials as it represents conditions of elastic deformation in relation to the loading of a material. This information allows having a measure of the evaluation of the competence of the material in terms of deformation. In turn, this quantity is usually used in several areas of engineering [1].

Traditionally, the estimation of the dynamic oung's modulus is carried out by means of destructive mechanical tests. However, these methods can be harmful and damage structures. A more efficient and sometimes faster alternative for determining this quantity is the use of non-destructive tests (NDT) by propagating acoustic waves [2].

Among these, two stand out, which are the impulse excitation and ultrasound methods. These use the propagation of high frequency sound waves that, when vibrating inside the materials, can provide estimated values for that magnitude [3].

According to Medeiros (2007) [4], the ultrasound technique has the potential to detect fissures, cracks, or superficial cracks in concrete structural elements. Additionally, through the acquisition arrangement by indirect transmission, it allows evaluating the location and estimating the depth of these pathologies.

This paper discusses two classical methods that relate material and acoustic properties to estimate the dynamic Young's modulus of specimens for concrete.

2. Theoretical Basis

The dynamic Young's modulus is one of the most important parameters used in structural calculation, especially in the design and structural evaluation phases. Several studies in the technical literature sought to correlate the propagation of the ultrasonic pulse in concrete and its resistance.

According to Garbacz and Garboczi (2003) [5], the development of NDT methods is an economically significant line of research, as it allows analysis and evaluations in loco, repeating the tests in the same regions as many times as necessary.

In the propagation method, an ultrasonic pulse is emitted by a transducer that is directed towards the material, which in the case of this research was concrete. This arrangement, known as direct transmission, is the most used in concrete acquisitions and was used in this research. Based on the time elapsed between the emitted pulse and the reflected pulse, it is possible to calculate the speed of sound in the material. The dynamic Young's modulus is obtained using the relationship between the speed of sound and the elastic properties of the material [6].

In the excitation impulse method, an impact is applied to the specimen, which can be automatic or manual; the acoustic pickup detects the acoustic response and transforms it into an electrical signal so that it can be processed by the hardware and software of the equipment. The modulus of elasticity is instantly obtained, according to the normative precepts of the standard [1]

It is noteworthy that these are just two examples of ultrasonic test methods for obtaining the dynamic Young's modulus. There are other methods available; the choice of the most suitable method depends on the material properties and test conditions.

3. Materials and methods

This research explores two classical acoustic emission techniques for estimating the dynamic Young's modulus. Two curing times were adopted to compare results: 14 and 28 days. The first one is the impulse excitation technique, using the Sonelastic® system. This method is based on ABNT-NBR 8522-2:2021- Hardened concrete - Determination of dynamic Young's modulus and deformation Part 2 [1]: dynamic Young's modulus by the method of natural frequencies of vibration. In this technique, the specimen is subjected to mechanical excitation by an impact drumstick, which can extract information measured by an acoustic measurement system, the value of the dynamic Young's modulus of the material instantly.

The other technique is the ultrasonic method, and in the case of this research, in the form of contact. It consists of the use of two low-frequency transducers, arranged on opposite sides of a sample, where acoustic waves are propagated longitudinally to the sample [9].

3.1. Sample preparation

Four different concrete mixtures were used according to Table 1. The preparation of the test specimens (TS) was carried out in cylindrical metallic molds with a diameter of 10 cm and a height of 20 cm. The mixtures consisted of crushed stone types 0 and 1, water, Portland [10] cement type III (CPIII), sand, and approximately 0.5% (relative to the weight of cement) of the superplasticizer additive Tec-Flow 9030.

The superplasticizer additive improved the fluidity of the mixture, facilitating the compaction and consolidation of the samples, which, in turn, contributed to improvements in the impermeability and strength of the concrete. In total, there were 4 concrete mixes: one mix for each reference f_{ck}, A, B, C, and D. Totaling 48 specimens, 12 specimens for each reference f_{ck}.

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 -D (30 MPa)	17,9	8,1	35,0	42,8	200,0
Mix -B (40 MPa)	21,8	8,2	33,5	40,9	200,0
Mix -C (50 MPa)	25,8	8,2	31,9	39,0	200,0

After the concrete curing period, the samples underwent measurements of the following physical quantities: diameter, height, density, and mass of each specimen. The dimensional measurements were taken with a caliper, while the mass measurements were performed using a Sartori electronic balance model CP 4202 S, with a capacity of 4200 g, and all measurements were conducted in three consecutive repetitions. They were then subjected to non-destructive tests to obtain the dynamic Young's modulus, using the ultrasound and impulse excitation technique. As shown below:

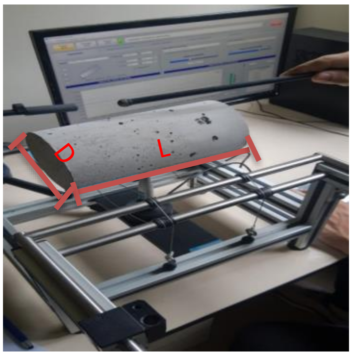
3.2. Impulse excitation method

All specimens were subjected to tests, where they were laid down and centered on the cables and a drumstick is tapped on the surface of the specimen, where this tap will generate a frequency that is identified by the Sonelastic® system.

$$E_d = 1{,}6067.\left(\frac{(L^3)}{(D^4)}\right).(m.F_f^2).T1 \quad (1)$$

Where: ***E*** is the dynamic Young's modulus, ***m*** is the cylinder mass, ***D*** is the cylinder diameter (mm), ***L*** is the cylinder length (mm), $\boldsymbol{F_f}$ is the fundamental resonant frequency of the cylinder in bending, and $\boldsymbol{T_1}$ is the correction factor for the fundamental bending mode considers the finite thickness of the cylinder, the Poisson ratio and so on [11].

Figure 01: The test specimen positioned on the cables of the Sonelastic® system, for obtaining the dynamic Young's modulus.



3.3. Ultrasonic contact method

A pair of flat-faced 50 kHz ultrasonic transducers from the Italian company Controls, specialized in construction products, was used. For ultrasonic tests on cementitious materials, the sensors must be coupled with the aid of coupling fluids such as honey, solid vaseline or grease or some high viscosity fluid.

For these measurements, each sensor was placed so that they were aligned on each of the flat faces of the cylindrical concrete samples. The couplant used was a grease based on calcium soap, mineral oils, and petroleum derivatives (brand: Graxa Iguaçu, Brazilian industry, suitable for lubricating parts

Figure 2 - Measurement of the specimen to obtain the ultrasonic velocity.

In this method, a transducer emits an ultrasonic pulse on the surface of the material and records the echo return time. Based on the return time and the speed of sound in the material, it is possible to calculate the dynamic Young's modulus with equation (2) [8,9,11,17]. Where **V** is the pulse velocity (m/s), **ρ** is the specific mass of the concrete (kg/m³) and **μ** is the Poisson coefficient, where the value of 0.20 is commonly used (DIÓGENES et al., 2011; BENETTI, 2012) [16].

$$E_d = V^2 . \rho . \frac{(1+\mu).(1-2\mu)}{(1-\mu)} \tag{2}$$

From the propagation distance and the transit time, it was possible to calculate the speed with which the acoustic signal traveled inside the sample, equation (3). Then, it is possible to obtain the dynamic Young's modulus using the expression. Where: **V** is the longitudinal ultrasonic velocity (m/s), **L** is the distance (m) between the transducer coupling points and **t** is the recorded time (s).

$$V = \frac{L}{t} \tag{3}$$

According to Pereira and Rodrigues (2010), techniques based on impulse excitation are more used for the characterization of brittle ceramic materials and for characterization at high temperatures, while the sonic velocity ultrasound wave propagation technique is more used for the characterization of metals and construction concrete [11].

4. Results

Table 2 brings together the results of the dynamic Young's modulus (E) and respective expanded uncertainty (U) for the impulse excitation and Ultrasonic method.

Table 2 - Table with the results obtained for the Ultrasonic Method and the Impulse Excitation Method - Sonelastic® system for 14 and 28 days.

RESULT: ULTRASONIC METHOD					**RESULT**: IMPULSE EXCITATION METHOD - SONELASTIC® SYSTEM			
	14 Days		**28 Days**		**14 Days**		**28 Days**	
CP (f_{ck})	*E* *(Gpa)* **Média**	*U* *(GPa)*	*E* *(Gpa)* **Média**	*U* *(GPa)*	*E* *(Gpa)* **Média**	*U* *(GPa)d*	*E* *(Gpa)* **Média**	*U* *(GPa)*
CP 20	29,05	0,5	31,91	0,5	25,4	0,5	27,9	0,5
CP 30	31,68	0,6	34	0,6	29,7	0,6	31,1	0,6
CP 40	34,07	0,7	35,85	0,7	35,47	0,8	36,9	0,7
CP 50	34,91	0,8	37,8	0,8	37	0,8	37,7	0,8

According to ISO GUM – Guide for expressing measurement uncertainty – Evaluation of measurement data, every result of a measurement can only be considered complete if it is accompanied by the associated uncertainty, i.e. measurement uncertainty [12].

Uncertainty is a fundamental criterion for establishing the quality with which these measurements are made and telling us how close they are to the expected value. Therefore, the greater the uncertainty, the lower the credibility of the results, in the same way that when the uncertainty is lower, the greater its 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 and worthy of reliability [13].

Regarding the analysis of the evolution of the Young dynamic module from 14 to 28 days, it was evident that there was growth for the four mixtures, as shown in Table 3.

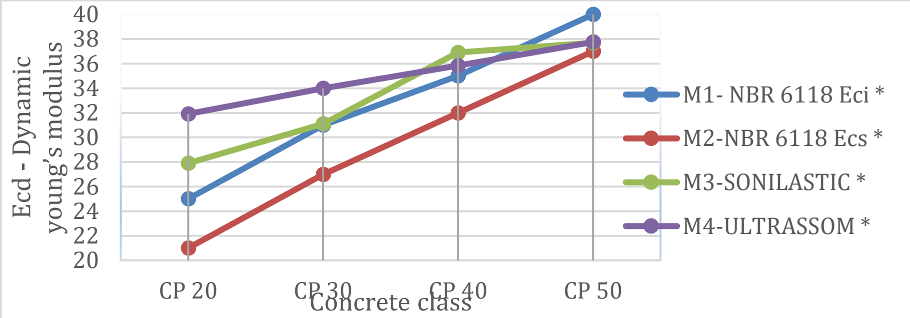
Table 3 presents the values indicated in standards for the static modulus of elasticity (M1) and dynamic modulus of elasticity (M2). In these tables, these values are compared with the values measured in this work for the Sonelastic impulse method (M3) and the ultrasonic method (M4). For all these methods, the Poisson modulus was considered the same and equal to 0.2.

Table 3 - Values from the NBR ABNT 6118 standard for the dynamic modulus of elasticity - ECd (M1), static modulus of elasticity - ECi (M2); ECd values for the impulse method (M3) and the contact ultrasound method (M4). Percentage relationships of values between methods and referring to the age of 28 days.

E_{cd} **- Dynamic elasticity modulus for 28 days (GPa)**									
Concrete class	**M1**	**M2**	**M3**	**M3/M1**	**M3/M2**	**M4**	**M4/M1**	**M4/M2**	**M4/M3**
CP 20	25,0	21,0	27,9	11,6%	32,9%	31,9	27,6%	52,0%	14,4%
CP 30	31,0	27,0	31,1	0,3%	15,2%	34,0	9,7%	25,9%	9,3%
CP 40	35,0	32,0	36,9	5,4%	15,3%	35,9	2,4%	12,0%	-2,8%
CP 50	40,0	37,0	37,7	-5,7%	1,9%	37,8	-5,6%	2,1%	0,2%

Note: M1 – NBR 6118 to E_{ci}; M2- NBR 6118 to E_{cs}; M3 – SONELASTIC; M4 – ULTRASOUND

Figure 3. Dynamic Young's modulus per concrete class



According to Metha and Monteiro (2014), the elastic modulus corresponds to a very small instantaneous deformation, approximately given by the initial tangent modulus traced from the origin. It is generally 20%, 30%, and 40% higher than the static elastic modulus for high, medium, and low-strength concretes, respectively [14].

From the percentage relationships in Table 3, it is possible to verify that METHA and Monteiro's (2014) percentage relationships, in general, distanced the static elastic modulus values more from the dynamic values than the two methods employed in this research. However, similarly to their findings, for high-strength concretes, the values obtained by both methods were closer to the static modulus compared to those of lower strength.

5. Conclusion

In Brazil, there is still no standard for determining the dynamic modulus of elasticity of concrete, only ABNT NBR 8802:2019 [15] which prescribes the non-destructive testing method for determining the speed of propagation of longitudinal waves, obtained by ultrasonic pulses in concrete.

When the modulus of elasticity of concrete is specified as a parameter for receiving and accepting a concrete structure, the measurement of this quantity by Brazilian laboratories is carried out by measuring the deformation of the concrete directly in the generatrix of the test piece.

Considering these facts and verifying the results of some studies already carried out to determine the dynamic modulus of concrete, through measuring the speed of ultrasonic waves or by the impulse stimulus method, it is understood that these can represent, for specific applications, a solution most suitable, mainly because it is a non-destructive method.

The results obtained by the two non-destructive mediation methods (M3 and M4) indicated the higher the concrete class, the lower the percentage differences (M3/M1) and (M4/M1) with the dynamic modulus of elasticity values (M1) recommended in the NBR ABNT 6118 standard.

This perspective encourages the carrying out of new experimental studies, with the aim of finding the most appropriate way of carrying out measurements for a more precise and rapid determination of this important quantity.

Therefore, it can be considered that the results presented provide promising results for the application of these methods to determine these properties in accordance with the results presented in the ABNT NBR 6118 standard [16].

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Acknowledgements

The authors thank the Brazilian National Council for Scientific and Technological Development (grants 307.562/2020-4); the Research Support Foundation of the State of Rio de Janeiro (grant E-26/210.687/2019, E-26/211.170/2019, and E-26/201.153/2021 [RCF])); Norte Energia S.A. (grant P&D ANEEL PD-07427-0421/2021).