ISSN 1061-8309, Russian Journal of Nondestructive Testing, 2022, Vol. 58, No. 4, pp. 277–288. © Pleiades Publishing, Ltd., 2022.
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ACOUSTIC METHODS

The Use of Ultrasonic Echo Pulse Velocity as an NDT Method to Predict the Concrete Strength and Uniformity

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Received February 4, 2022; revised February 18, 2022; accepted February 18, 2022

Abstract—The ultrasonic approach is one of the non-destructive testing methods that most technologically progressed in past few years. This study aims to validate the accuracy and capabilities of this method in the mechanical characterization of concrete elements, by using an ultrasonic tomography equipment based in echo pulse velocity (S-waves). The elastic modulus and compressive strength of concrete are estimated from the echo pulse velocity. Furthermore, the uniformity of concrete elements is evaluated. The concrete compression strength prediction was performed on cubic specimens and the reached accuracy was over 91% using the analytical approach proposed on this study. The correlation coefficient between the pulse echo velocity and the uniaxial compression strength found in this study was over 97%. Thus, the use of the ultrasonic NDT to evaluate the uniformity of concrete elements proved to be efficient.

Keywords: NDT methods, concrete structures, ultrasonic echo pulse, S-waves

DOI: 10.1134/S1061830922040039

1. INTRODUCTION

Concrete is the single most widely used construction material in the world, simply as a mixture of cement, water, and aggregates or as a modern concrete containing more and more mineral components, chemical admixtures, fibres, etc. [1]. Concrete is a structural material with a high variability of characteristics, even using similar production parameters and same raw materials [2]. Whereas this variability, the European standard EN 206-1 [3] establishes that all produced concrete must be subjected to production control, additionally its compression strength must be attested. The concrete is expected to reach the design strength at the age of 28 days. Usually, the strength evolution is monitored by the use of destructive tests on specimens made from the same concrete batches used at the construction site. However, the tests results are obtained under controlled laboratory conditions and may not reflect the real in situ concrete characteristics [4, 5].

In order to assess the *in situ* concrete mechanical characteristics, non-destructive testing (NDT) methods appears as an interesting approach, since they give access to material properties while remaining rapid and of moderate cost [5]. Even though the core drilling test has become the most effective method to estimate directly the *in situ* compressive strength of concrete [6], in some situations this technic may not be recommended or even not possible [7, 8]. In addition, this minor-destructive test (MDT) requires more labour hours and it is not viable to perform the sampling over large areas [9]. On the other hand, NDT technologies have been experiencing advancements in recent years, their costs are reducing, and the interest is increasing [10]. The growing interest in NDT can be also attributed to the need to assess existing structures [11]. Such assessment is required in various contexts: (a) when some damage has developed through time, (b) when new requirements have to be addressed, due to changes in regulations or in the loads to be supported, (c) when the material condition must be checked because of some suspicion [5].

Another advantage associated to the portables NDT is the fact that an increase of measurements represents a minimal increase to the test cost [12]. However, these methods provide information about physical properties that are correlated to mechanical properties, unlike destructive tests which provides the mechanical characteristics in a direct way [11]. Due to the quality of estimation that may be affected by

Fig. 1. Conventional ultrasonic equipment (CUE).

some errors and uncertainties, the European standard EN 13791 [13] establishes that the NDT methods must be calibrated with core tests results.

The use of ultrasonic equipment as an NDT method had a considerable development in recent years and, as a great advantage, it is performed with a portable equipment. It is used *in situ*, directly on the structure, without causing any damage, which makes it an important tool to improve the quality control and to assist in the characterization and diagnosis of existing structures.

A conventional ultrasonic equipment (CUE) determines the velocity that a longitudinal, or compression, wave (P-wave) passes through the concrete. The procedure to measure this velocity is established by the European standard EN 12504-4 [14]. With this velocity, it is possible: (i) to estimate the dynamic elastic modulus; (ii) to determinate the uniformity of a concrete element, or of parts made of the same concrete batch; (iii) to follow the internal changes of properties over time; (iv) to evaluate the quality control; and (v) to estimate cracks depths [14].

This study aims to validate the precision and the capabilities of the testing method to estimate the mechanical properties of concrete elements by using a modern ultrasonic tomography equipment (UTE), which determines the pulse velocity of transverse, or shear, waves (S-wave), unlikely the traditional equipment. It is expected that the UTE can provide more representative data when compared with the CUE.

2. THE ULTRASONIC TESTING METHOD

The first studies reports involving mechanically generated pulses through concrete are dated from the mid-1940s of the 20th century [15]. The main conclusion reported from the first studies is the fact that the velocity of an ultrasonic pulse through a solid material depends essentially on its elastic properties [15] allowing to indirectly estimate the mechanical properties of concrete, namely its compression strength.

The ultrasonic tests are carried out using an apparatus commercially known by the term PUNDIT (portable ultrasonic nondestructive digital indicating tester) [12]. The conventional ultrasonic equipment (Fig. 1) measures the velocity of P-waves [12, 16].

The main application of the non-destructive ultrasonic method is the possibility to estimate the elastic modulus of the concrete. This estimation is done by using the ultrasonic pulse velocity of the P-waves, applying Eq. (1) [17]

$$E_{\mathrm{d}} = \frac{V^2 \rho}{K}. \quad (1)$$

In Eq. (1), E_{d} is the dynamic elastic modulus expressed in Pa, V is the compression pulse velocity (P-waves) in m/s, ρ is the density of the concrete in $\mathrm{kg/m^3}$ and K is a constant that depends on the Poisson's ratio, ν, according to Eq. (2)

$$K = \frac{(1-\nu)}{(1+\nu)(1-2\nu)}. \quad (2)$$

In the present study, the equipment used was the PL-200PE from Proceq, an UTE (Fig. 2) which measures the velocity of S-waves. The S-waves have the advantage to be more statically stable than the P-waves [18].

Fig. 2. Ultrasonic tomography equipment (UTE).

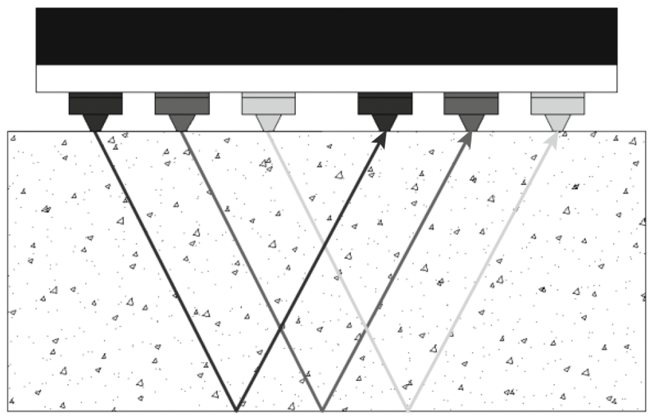

Fig. 3. The operating principle of an UTE.

The operating principle is based on measuring the transmission interval of emit an ultrasonic pulse through a solid and receiving the respective echo. Each one of the nine transducers on the left side of the handle, as shown in Fig. 2, is paired with a respective transducer on the right. The transmitting transducers, located on the left side, emits ultrasonic pulses constantly, while the receiving transducers, located on the right side, receives the corresponding echoes, as shown in Fig. 3 [19, 20].

The pulse velocity measured with the UTE is obtained by the individual interpretation of the nine pairs of transducers [19]. Using this equipment, the tests results from a single measurement will be more representative than the results using the CUE, which has only one transmitting transducer and one receiving transducer, and the measured pulse velocity is obtained from only one direct path.

The first step of this study was to enable the analytical concrete strength estimation using the pulse velocity obtained by the UTE (S-waves), as it is possible using P-waves.

As the propagation principle of P-waves and S-waves are different, they do not propagate in the concrete with the same velocity. Scott [21] indicates that the S-waves have approximately 60% of the velocity of P-waves. Similar relation between the S-waves and P-waves velocities was found on the studies carried out by Birgül [22] and Lee and Oh [23].

The internal moisture of the concrete interferes at the P-waves velocity, Bungey et al. [15] indicates the velocity increases around 5% when compared with dry concrete, meanwhile S-waves do not pass through gaseous and liquid medium, which means that the internal moisture does not affect its velocity [24].

Other variables affect the pulse velocity of both types of waves. Ravindrarajah [25] and Elvelry and Ibrahim [26] attested on their studies that the type of cement influences the pulse velocity, Elvery and Ibrahim [26] even attested that this influence is higher at early ages, and it can compromise the accuracy to establish a relation between pulse velocity and concrete strength. Evangelista [27] on her study concluded that the type of cement can change the pulse velocity in a rate of approximately 5%.

Table 1. *s* values according to the type of cement

s values	Type of cement
0.20	CEM 42.5R, CEM 52.5 N, CEM 52.5R (Class R)
0.25	CEM 32.5 R, CEM 42.5 N (Class N)
0.38	CEM 32.5 N (Class S)

Source: Adapted from EN-1992 [29].

Lee and Lee [28] concluded on their studies that the presence of coarse aggregate has some significant influence at the pulse velocity on concrete at early ages, the pulse velocity was found to be 16% higher at the concrete than at the mortar. However, Silva et al. [18] attested by their study that the amount of coarse aggregate has no significant influence at the pulse velocity. Temperature, if inside the serviceability range, and stress level, besides overstress situations, are variables that does not affects in a significant way the pulse velocities [15, 26].

In order to overcome the factors that affects the pulse velocity and enable the use of S-waves to estimate the concrete strength, this study purposes alternatives to Eq. (1), where the variable V should be changed as shown in Eqs. (3) and (4). Equation (3) is adequate for concrete aged between 3 and 28 days and Eq. (4) for concrete aged over 28 days

$$V = 1.65V_{\text{echo}}\exp(0.48sj^{-0.1}), \tag{3}$$

$$V = 1.65V_{\text{echo}}\exp(0.3439s). \tag{4}$$

In Eqs. (3) and (4), V is the compression pulse velocity (P-waves), V_{echo} is the echo pulse velocity measured by the UTE (S-waves) expressed in m/s, s is a coefficient that depends on the type of cement as shown in Table 1 and j is the age of the concrete in days.

The proposed analytical method allows the estimation of the dynamic elastic modulus of concrete using the echo pulse velocity (S-waves) provided by the UTE, through the application of the modified Eq. (1). The dynamic elastic modulus E_{d} estimated by the ultrasonic pulse velocity is equivalent to the tangent elastic modulus, E_c [30]. According to the EN 1992 [29], through the tangent elastic modulus, it is possible to calculate the secant elastic modulus, E_{cm}, of the concrete using Eq. (5)

$$E_c = 1.05E_{\text{cm}}. \tag{5}$$

With the secant elastic modulus, the compressive strength can be calculated using Eq. (6) reproduced from the EN-1992 [29]

$$E_{\text{cm}} = 22\left(\frac{f_{\text{ck}} + 8}{10}\right)^{0.3}. \tag{6}$$

In Eq. (6), E_{cm} is the value of the elastic modulus in GPa and f_{ck} is the characteristic compressive cylinder strength of concrete.

3. EXPERIMENTAL PROGRAM

In order to verify the effectiveness of this equipment and the proposed analytical method to allow the use of Eq. (1) with S-waves, the adequate procedure is to assess the results provided by UTE under laboratory conditions. Thus, the objective of the experimental program presented here is to test specimens of normal concrete mixture of cement, water and normal aggregates.

3.1. Specimens Preparation

The materials selected for test specimens were a Portland Lime Cement from Secil company classified according to EN 197-1 [31] as CEM II B/L-32.5, granite gravel 8/14, natural sand 0/4 and water.

For the experimental program 18 cubic concrete specimens with dimensions 15 × 15 × 15 cm and 3 prisms with dimensions 15 × 15 × 55 cm were produced in the laboratory of Polytechnic Institute of Bragança. Three different mixes were produced and identified as M1, M2, and M3. The proportions of sand, gravel and water relating a cement unit, in mass, used for each mix are shown in Table 2.

Table 2. Proportions, in mass, to produce the concrete mixtures

Proportions	Cement	Sand	Gravel	Water
M1	1	1.28	2.28	0.40
M2	1	1.95	2.95	0.50
M3	1	1.28	2.28	0.55

The viscosity of the mixtures was evaluated through the slump flow test. All the concrete mixtures presented a consistency class S1, according to the standard EN 12350-2 [32]. Six cubic specimens were produced, labelled from one to six, for each concrete mix. The cubic specimen no. 1, made with concrete mix M1 was identified as C1-M1 and the others were identified as (C*n*-M1, C*n*-M2, and C*n*-M3 with $n = 6$) following the same logic.

From the three prisms produced, two were made with the M2 concrete mix (identified as P1-M2 and P2-M2) and one with the M1 concrete mix (P1-M1).

The cubic specimens (C*n*-M1, C*n*-M2, and C*n*-M3) were cured after de-moulding at a temperature $T = 20°\text{C}$ and 90% of relative humidity R.H. After 28 days of curing, uniaxial compression tests were performed with load control in a compression machine from Matest.

The prismatic specimens (P1-M1, P1-M2, and P2-M2) were also cured after de-moulding at a temperature $T = 20°\text{C}$ and 90% of relative humidity R.H. until 28 days of age. After that, they were exposed to the laboratory atmosphere conditions until the age of 90 days. For theses specimens, the ultrasonic and the compression tests were performed at the age of 90 days.

The mechanical tests on the prisms required then to be cut in three equal cubic specimens of dimensions 15 × 15 × 15 cm (a remnant part of 15 × 15 × 10 cm was discharged). Measurements with the ultrasonic equipment were done before and after the cut of the prismatic specimens.

3.2. Test Methodology

First the cubic specimens (C*n*-M1, C*n*-M2, and C*n*-M3) were tested with the UTE and the V_{echo} was measured. The results were used to analytically estimate the elastic modulus and compressive strength of the concrete. The V_{echo} was measured in three regions of each specimen, at the top, at the bottom and at the centre (Fig. 4), the most stable was considered the representative. Measurements were performed at ages of 3, 7, 14 21 and 28 days.

The prismatic specimens (P1-M1, P1-M2, and P2-M2) were tested at the age of 90 days. Three measurements were made with the objective to have a perspective about their uniformity. The location of these measurements was in the centre of the further cuts (Fig. 5).

The sections of the prismatic specimens (P1-M1.*n*, P1-M2.*n*, and P2-M2.*n* with $n = 3$) were also tested for ultrasonic pulse velocity after cut in order to estimate the elastic modulus and the compressive strength more accurately for each of these sections.

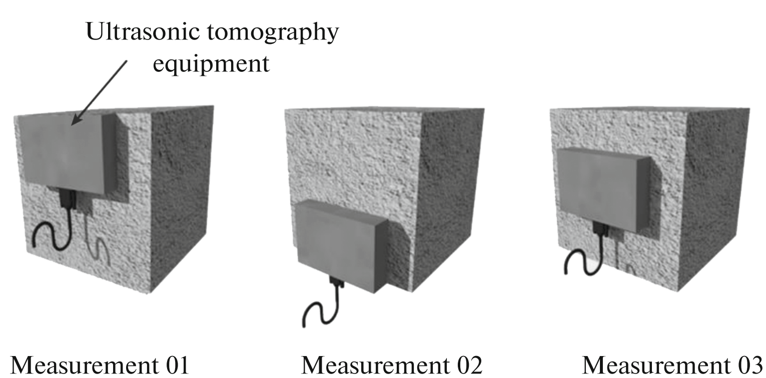

Fig. 4. Representation of the measurement places with UTE at the cubic specimens.

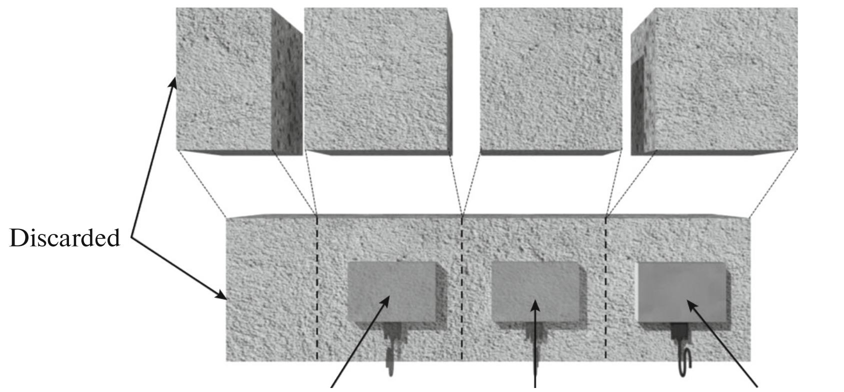

Fig. 5. Representation of the location of the pulse velocity measurements on the prismatic specimens to check uniformity foreseeing future cuts.

4. RESULTS AND DISCUSSIONS

4.1. Cubic Specimens

The results of the pulse velocity measurement tests were used to estimate the elastic modulus and the compressive strength of the specimens.

Firstly, Eq. (3) was used and the results obtained replaced the variable V in Eq. (1). The estimated dynamic elastic modulus was divided by 1.05 in order to obtain the secant elastic modulus of each specimen. The characteristic compressive strength, f_{ck}, was calculated for each specimen using Eq. (6) according to the EN-1992 [29].

The characteristic cube compressive strength of each specimen ($f_{ck, cube}$) was calculated by using numerical interpolation, considering the section of Table 3.1 from the EN-1992 [29] as show in Table 3.

Table 4 presents the results of the secant elastic modulus (E_{cm}), the compressive strength (f_{ck} and $f_{ck, cube}$) estimated by the analytical method (AM) through the ultrasonic pulse velocity and the compressive strength ($f_{ck, cube}$) obtained by the destructive compression test (DCT).

Table 4 shows that the estimative of the compressive strength by the ultrasonic pulse velocity had errors ranging from –4.40 to 8.95%. Using the measured V_{echo} (S-waves) by the UTE and the compressive strength obtained by the destructive test, a linear adjustment was made between these two obtained values, as shown in Fig. 6.

The graph shows that it was possible to establish a correlation coefficient between the ultrasonic echo pulse velocity and the compressive strength of the concrete higher than 97% with a confidence degree higher than 94%, through a linear adjustment.

Figures 7–9 shows a comparison between: (a) the strength evolution curve analytically calculated through the ultrasonic pulse velocity measurements at the ages of 3, 7, 14, 21, and 28 days; (b) a retroactive analysis from the destructive test using Eq. (7) from the Eurocode 2 [29]

$$f_{ck}(t) = (\beta_{cc}(t) f_{cm}) - 8. \tag{7}$$

In Eq. (7), $f_{ck}(t)$ is characteristic compressive strength in MPa for an age t, f_{cm} is the characteristic compressive strength obtained from the destructive test and $\beta_{cc}(t)$ is obtained by Eq. (8)

$$\beta_{cc}(t) = \exp\left\{ s\left[1 - \left(\frac{28}{t} \right)^{1/2} \right] \right\}. \tag{8}$$

In Eq. (8), t is the concrete age in days and s is a coefficient that depends on the type of cement as shown in Table 1.

Table 3. Section from Table 3.1 from the EN-1992 [29]

Class	C12/15	C16/20	C20/25	C25/30	C30/37	C35/45	C40/50	C45/55
f_{ck} [MPa]	12	16	20	25	30	35	40	45
$f_{ck, cube}$ [MPa]	15	20	25	30	37	45	50	55

Table 4. Elastic modulus and compressive strength of the cubic specimens estimated by ultrasonic pulse velocity, compressive strength obtained by destructive test and respective errors

Specimen	V_{echo}, m/s	E_{cm}, GPa	f_{ck} (AM), MPa	$f_{ck,\ cube}$ (AM), MPa	$f_{ck,\ cube}$ (DCT), MPa	Error
C1-M1	2139	33.3	31.7	39.8	38.0	4.63%
C2-M1	2098	32.0	26.9	32.7	34.8	–6.12%
C3-M1	2116	32.6	29.0	35.6	35.5	0.19%
C4-M1	2116	32.6	29.0	35.6	35.7	–0.24%
C5-M1	2083	31.6	25.3	30.4	31.7	–4.10%
C6-M1	2083	31.6	25.3	30.4	31.1	–2.25%
C1-M2	2055	30.7	22.4	28.0	27.5	1.81%
C2-M2	2055	30.7	22.4	28.0	27.8	0.72%
C3-M2	2069	31.1	23.8	29.8	28.1	6.05%
C4-M2	2083	31.6	25.3	30.4	29.0	4.83%
C5-M2	2028	29.9	19.9	24.8	25.6	–2.85%
C6-M2	2055	30.7	22.4	28.0	28.2	–0.71%
C1-M3	2013	29.5	18.5	23.1	22.9	0.87%
C2-M3	2055	30.7	22.4	28.0	25.7	8.95%
C3-M3	2041	30.3	21.1	26.4	24.3	8.64%
C4-M3	2041	30.3	21.1	26.4	24.6	7.32%
C5-M3	2027	29.9	19.8	24.7	23.3	6.17%
C6-M3	2000	29.1	17.4	21.7	22.0	–1.28%

It is possible to observe in the graphs from Figs. 7–9 that the concrete strength evolution curve analytically calculated with the ultrasonic pulse velocities showed a similar behaviour with the retroactive analysis carried out from the compressive destructive test. Most of specimens presented an almost constant error during the concrete aging until 28 days.

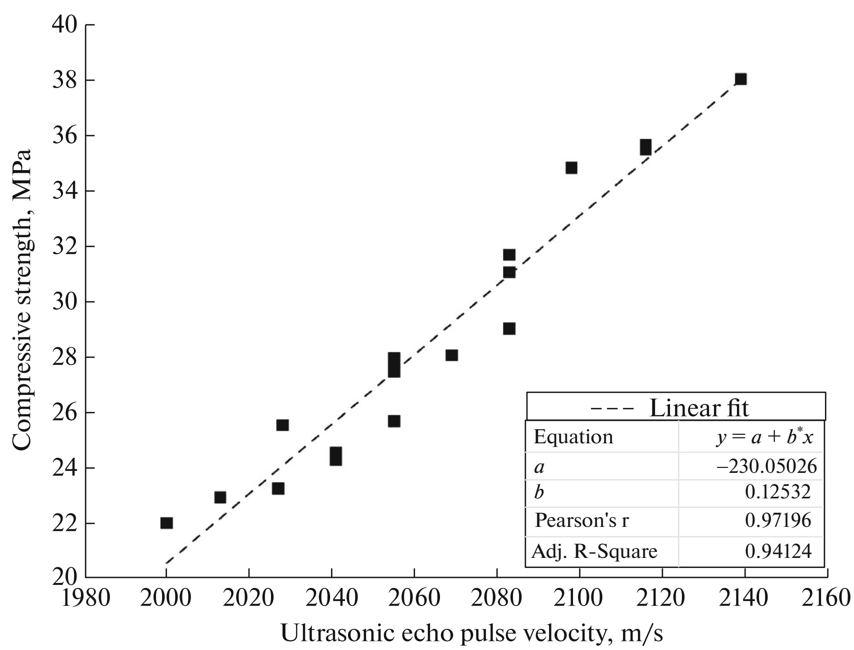

Fig. 6. Linear adjustment.

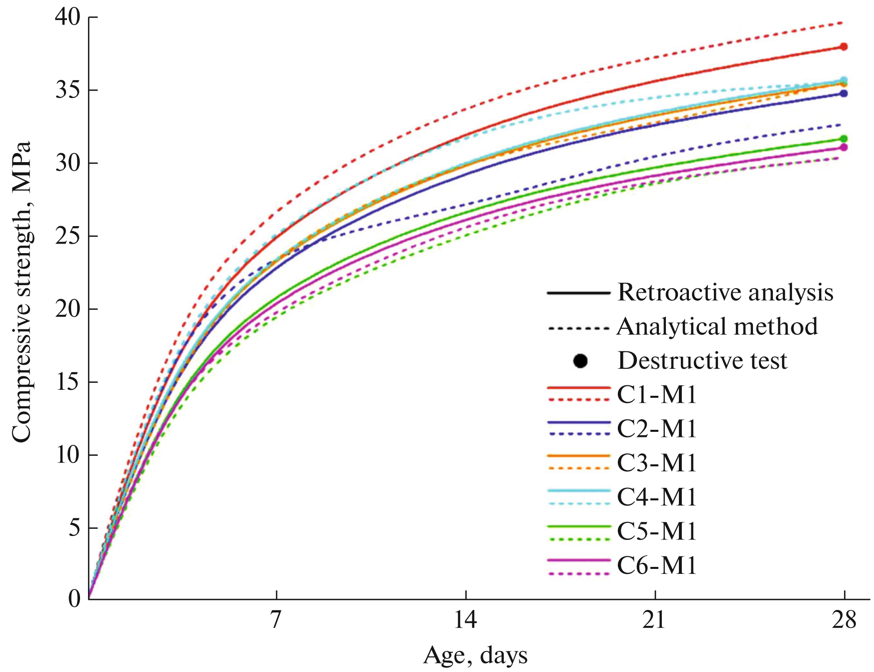

Fig. 7. Compressive strength evolution curve—retroactive analysis *x* analytical method for specimens made from the concrete mix M1.

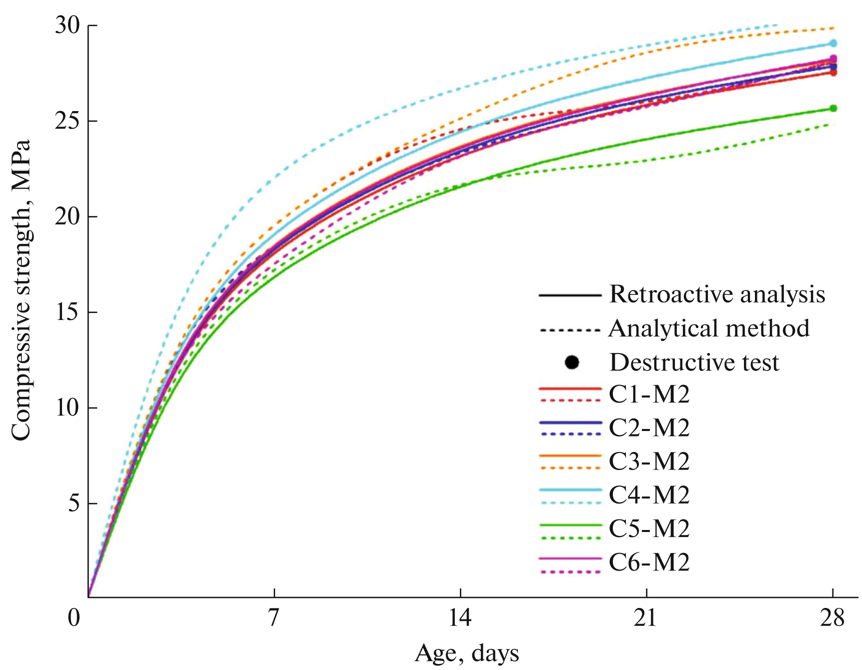

Fig. 8. Compressive strength evolution curve—retroactive analysis *x* analytical method for specimens made from the concrete mix M2.

4.2. Prismatic Specimens

The first test performed with the prismatic specimens was the check of uniformity before the cut. Three measurements of the pulse echo velocity were performed at the centre where the further cuts in the prisms would be made, as shown in Fig. 5. Figure 10 shows the results obtained for the three specimens in a schematic and graphic representation.

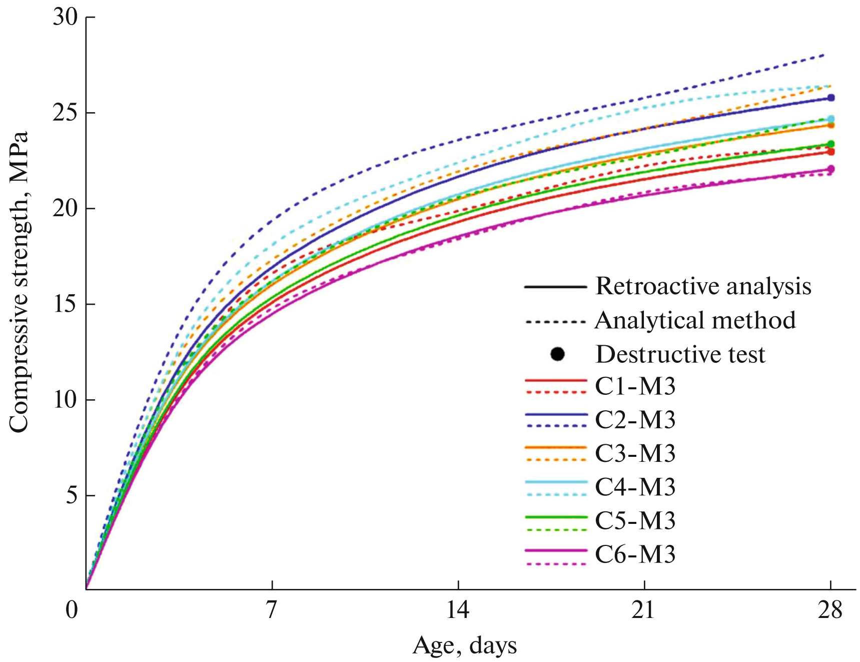

Fig. 9. Compressive strength evolution curve—retroactive analysis *x* analytical method for specimens made from the concrete mix M3.

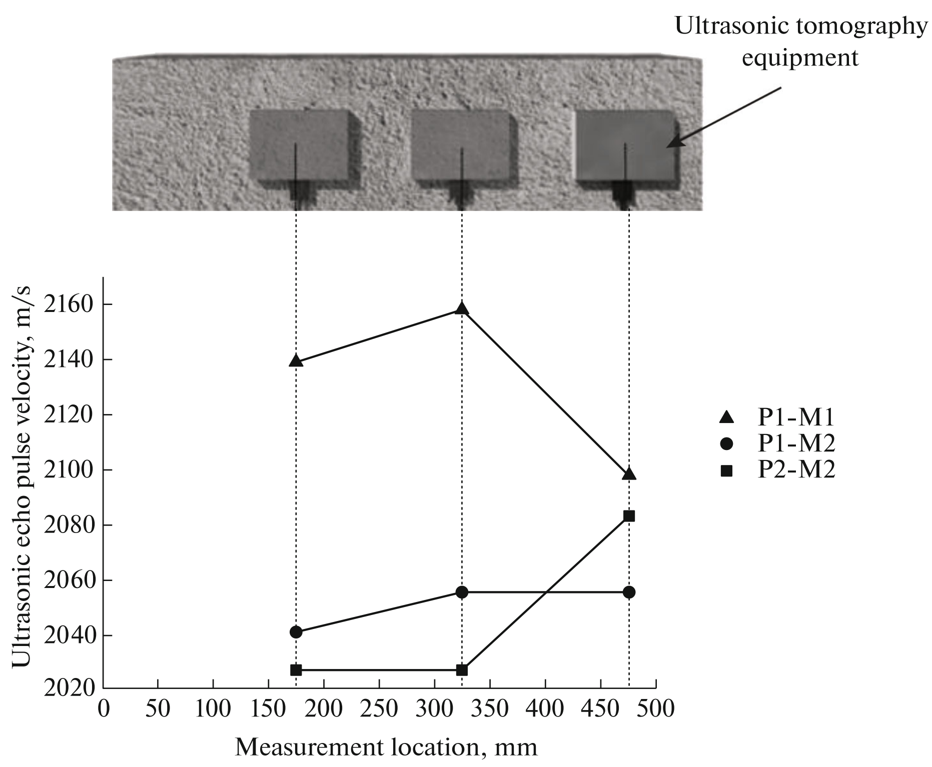

Fig. 10. Schematic and graphical representation of the uniformity test using the UTE.

The results shown in Fig. 10 leads the assumption that the P1-M2 prism presents good uniformity, the P1-M1 prism presents moderate uniformity and the P2-M2 prism presents low uniformity.

After the uniformity test the prismatic specimens were cut in three pieces of dimensions 15 × 15 × 15 cm, and a surplus of dimensions 10 × 15 × 15 cm that was discarded. The ultrasonic echo pulse test was per-

Table 5. Compressive strength of the parts of the prismatic specimens estimated by the ultrasonic echo pulse velocity, compressive strength by destructive testing and respective errors

Specimen	V_{echo}, m/s	E_{cm}, GPa	f_{ck} (AM), MPa	$f_{ck,\ cube}$ (AM), MPa	$f_{ck,\ cube}$ (DCT), MPa	Error
P1-M1.1	2139	33.3	31.7	39.8	39.5	0.74%
P1-M1.2	2158	33.9	34.1	43.6	42.2	3.39%
P1-M1.3	2116	32.6	29.0	35.6	36.3	–2.02%
P1-M2.1	2041	30.3	21.1	25.5	26.7	–4.49%
P1-M2.2	2055	30.7	22.4	27.2	27.4	–0.73%
P1-M2.3	2055	30.7	22.4	27.2	27.3	–0.37%
P2-M2.1	2027	29.9	19.8	24.7	25.2	–2.14%
P2-M2.2	2013	29.5	18.5	23.1	23.2	–0.33%
P2-M2.3	2083	31.6	25.3	30.4	33.0	–7.80%
P1-M1.1	2139	33.3	31.7	39.8	39.5	0.74%
P1-M1.2	2158	33.9	34.1	43.6	42.2	3.39%
P2-M2.3	2083	31.6	25.3	30.4	33.0	–7.80%

formed again, this time according to Fig. 4, in each of the three sections of the prisms. The sections of the prisms were numbered from left to right; the discarded part was located at the far left.

Table 5 presents the results of the tests with the UTE after the cut of the prismatic specimens. Table also shows the V_{echo}, the secant elastic modulus calculated by Eq. (1) (which result was divided by 1.05) where the variable V was substituted by the result of Eq. (4), the compressive strength calculated by Eq. (6) reproduced from the EN-1992 [29], the compressive strength obtained by the destructive test and respective errors. The tests took place at the age of 90 days.

The estimative of the compressive strength by the ultrasonic tests in the sections of the prisms and the compressive strength verified in the destructive test present errors ranging from –7.80 and 3.39%, which shows a good precision. Only in two sections (P1-M1.3 and P2-M2.2) the echo pulse velocity measured changed after the specimens were cut. Therefore, according to the hypothesis raised after the first check of the uniformity, it was possible to confirm by the destructive compression test that the P1-M2 prism was a specimen that presented good uniformity, the P1-M1 prism had a moderate uniformity and the P2-M2 had a low uniformity.

5. CONCLUSIONS

This study made possible to understand the potential of a modern-day UTE to perform the mechanical characterization of concrete. The equipment that was used on this experimental program works with shear waves (S-waves), differently from the CUE that usually measures compressive waves (P-waves). The following conclusions were achieved:

• Through the analytical method proposed on this study, by a modification on Eq. (1) to enable the use of S-waves pulse velocities to estimate the dynamic elastic modulus, it was possible to reach an accuracy of over 91% in the concrete compressive strength prediction.

• The echo pulse velocity (V_{echo}) showed a strong linear correlation with the compressive strength, a correlation coefficient higher than 97% with a confidence degree higher than 94% were reached.

• The evaluation of the concrete uniformity proved to be possible and accurate. The measurements remained consistent for the prism before and after cut, only two pieces (out of nine) presented changes on its ultrasonic pulse velocities. Nevertheless, these changes were less than 1%.

• The analytical method is applicable even if the user has no information about the cement type, a medium value of s from Table 1 could be use in Eqs. (3) and (4). However, it will decrease the accuracy of the compressive strength prediction in up to 8%.

• The NDT method of ultrasonic pulses proved to be an interesting approach to monitoring the evolution of the concrete compressive strength.

• The water/cement ratio do not affect the confidence degree to establish a correlation between the ultrasonic pulse velocity and the concrete compressive strength.

Conducting experiments with the ultrasonic equipment showed that, when it is performed in a meticulous and systematic way, this method is a very advantageous non-invasive NDT. However, it is important to indicate that the UTE shows a high sensibility, the results change with a slight change in the pressure applied on the transducers. A competent user, used to the device, is required to reach reliable results.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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