Correlating ultrasonic pulse velocity and compression resistance of dry concretes at 54 kHz and 500 kHz

E W J Santos, E S F Pinto, F D G Santos, T C Dourado, R P B Costa-Félix
Laboratory of Ultrasound (Labus), National Institute of Metrology, Quality and Technology (Inmetro), Brazil, RJ
ericleswilliam@gmail.com; rpfelix@inmetro.gov.br

Abstract: Nondestructive tests applying ultrasound in concrete is used for more than half-century. However, the difficulties in making transit time measurement in heterogeneous media have limited the spread use of these applications. The objective of this work is to present a metrological protocol to determine the correlation between the compressive strength of concrete specimens with about 1 year of cure with their respective longitudinal ultrasonic pulse velocity (UPV). From excitation signals sent through a tunable square wave using the direct transmission method, two pairs of transducers with central frequencies of 54 kHz and 500 kHz were used. UPV is determined by the relation between the length and the propagation time of flight the waveform travels within the concrete test specimens. The pieces were constructed according to ABNT NBR 5738:2015 (Concrete – Procedure for molding and curing of concrete specimens) and tested for compression according to ABNT NBR 5739:2007 (Cylindrical specimen compression test – Method of the test). The preliminary results obtained discloses a coherent increase in UPV and concrete strength. Moreover, the highest frequency leads to higher UPV. With the findings presented in this paper, it is possible to define a dual-frequency nondestructive ultrasound method to evaluate concrete resistance more reliable than the traditional approach.

1. Introduction
The concrete is the most used constructive element in the word in the building industry, and also the higher CO₂ emitter [1]. There are worldwide concerns regarding concrete use, maintenance, and sustainability, including the material’s lifetime improvement [2].

Nondestructive testing (NDT), highlighting the ultrasonic ones, have been requested for civil construction for a long time to do quantitative and qualitative evaluations of the concrete structures [3]. Several works analyzed the concrete resistance from regression curves empirically correlating the rupture limit to the compression of concrete specimens and their longitudinal ultrasonic pulse velocity (UPV) [4][5][6]. The equations derived from the correlation may be generic, when a larger range of concrete may be employed, or specific for a determined type of concrete [5]. In this case, it is similar to a calibration curve. Ultrasonic NDT is not as widely used as it could be if compared to other industrial applications. The great variation of concrete makes ultrasonic NDT not reliable enough, which is an important drawback. Furthermore, the UPV in inhomogeneous media, as concrete is by its nature, is not easy to measure, encompassing another important restriction to the spread use of ultrasonic NDT [3].
This article explores the ultrasonic NDT method and good UPV measurement practices already disclosed in the technical literature of ultrasonic testing on concrete from a metrological protocol for UPV measurement, relating it to the compressive strength of concrete.

2. Theoretical review

2.1 Ultrasonic velocity
The measurement of time of flight (ToF) of longitudinal ultrasonic pulses, also known as a compressional or primary wave, is a necessary step to assess the ultrasonic pulse velocity (UPV) in any material, including concrete test specimens [7]. The other quantity to define UPV is the length of the path traveled by the front wave, as UPV is the ration between the length and the ToF.

The concrete is a heterogeneous material and may have much dissimilar composition. The curing process, on its turn, may also vary for different concretes or applications, which multifold the possible final characteristics. Besides, what has been found and cannot be overlooked is that during its useful life concrete transforms such as variations in volume, temperature, humidity, etc., which makes it complex and full of traits [6]. Among many possible parameters to characterize concrete, the specialized technical literature adopted the ToF as the most reliable quantity to assess UPV. As one can easily understand, ToF depends intrinsically on the composition of the concrete, including the aging process and other aspects that make each concrete piece unique. Nevertheless, it is possible to relate UPV and the most important characteristics of concrete: its resistance to compression.

2.2 Ultrasonic propagation
The technical standard ISO 1920-7:2004 [8] presents three different methods (or arrangements) to assess the speed of sound, according to the access to the concrete surfaces to be tested. The arrangement is defined as a function of the relative position between the two transducers, named direct, semi-direct, and indirect. In this work, direct transmission is adopted. It is worth mentioning that the direct transmission method is the most recommended one, as it is easier to directly derive longitudinal UPV from ToF.

2.3 Constructions of regression curves
Several researchers had studied how to assess UPV in heterogeneous materials like concrete. Panzera and colleagues [4] showed that the correlation between UPV and compression strength allows the creation of regression curves to quantitatively qualify different kinds of concrete. Different equations have been developed in which the exponential model seems to be the best one. In the works of Turgut and Kucuk [3] and Nash’n’t et al [6] these equations are disclosed.

Garbacz and Garbočzi’s [9] studied ultrasonic NDT to assess polymer composite properties, such as anti-corrosion protection and pre-cast elements, relating UPV and the pull-over strength. Moreover, they evaluate the adhesion between the polymer coating and the concrete substrate. The equations presented therein show the reference from zero to the maximum adhesion rate.

3. Materials and methods
For this work, 9 cylindrical concrete specimens were molded according to the technical standard ASTM C 31 [10]. They have been tested with about a year of drying. The samples corresponding to two different types of concrete. The first group with 5 samples of regular concrete and the second with 4 samples containing coarse aggregate (stone) from recycled materials.

3.1 Uncertainties assessment.
Uncertainties were assessed following the Guide to the Uncertainty in Measurement, GUM [11]. The metrological model defines the sources of uncertainty to be considered [12]. In this work, type A uncertainty derived from 30 repeated measurements of the ToF (t), 12 measurements of length (s), and one destructive test of breaking load (Fc) for each sample. It is noteworthy the larger variability of results of temporal magnitude concerning dimensional. So, it demands a larger number of collections of the first one for improvement in statistical quality. It is evident in
ultrasonic velocity measurements of heterogeneous materials, Type B uncertainties were extracted from the calibration certificate of the respective equipment [13]. For uncertainties of type A, when the number of samples was more than two:

\[
U_A = \frac{sd}{\sqrt{n}}
\]  

(1)

in which \(sd\) is the standard deviation and \(n\) corresponds to the number of measurements for each quantity. When the number of measurements was two, each with a measured value of \(M_1\) and \(M_2\), then the type A uncertainty is assessed by:

\[
U_A = \frac{|M_1 - M_2|}{\sqrt{12}}
\]  

(2)

Calculus of expanded uncertainty (\(U\)) starts with the determination of combined standard uncertainty and has been reported according to [11], as follows:

\[
u_z^2 = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 u_{x_i}^2
\]  

(3)

in which \(u_z\) is the combined standard uncertainty associated with the outcome of the measurement (or calculation) \(f\), and \(u_{x_i}\) the standard uncertainty, associated with each variable \(x_i\) used to express the value of \(f\).

Lastly, the expanded uncertainty (\(U\)) can be calculated by:

\[
U = u_z \cdot k
\]  

(4)

where \(k\) is the coverage factor which corresponds to a level of confidence defined by 95%.

3.2 Ultrasonic pulse velocity

The direct transmission method was done with a pair of transducers for each frequency selected. For 54 kHz, transducers model 58-E4800 and an ultrasonic equipment model 58-E0048 (CONTROLS, Italy), while for 500 kHz a pair of transducers with 32 mm in diameter (model V-389) and another with 25 mm in diameter (model A-301S), both manufactured by Panametrics-Olympus NDT (USA). The signal was generated by flaw detector EPOCH 600 (Olympus NDT, USA), and the equipment was also used to determine the ToF [14].

The length was measured with a calibrated caliper, series 500, Absolute AOS Digital Model (Mitutoyo, Japan), with a standard uncertainty of 0.03 mm.

The ultrasonic transducers were positioned in the opposite flat surface of the cylinder to measure the ToF, following the requirements of item 6 of ISO 16831:2012 [15].

To properly position the transducer upon the cylinder surface, a special jig was designed and printed in a 3D printer (see Figure 1). The jig assures the distance from the edge of the cylinder under standard requirements. For each point, two sequential ToF readings were performed decoupling and coupling the transducers. Solid vaseline was used to coupling the transducers on the concrete cylinder surface. Those two readings should not be more than 0.5% divergent. If that was the case, another set of two readings were performed at the same point, and the result is the average of those readings. That procedure was repeated in 5 different points in each sample. One ToF result is the average of the ToF for those points. The whole procedure was repeated 5 times, being the Type A uncertainty assessed thereafter. The procedure was repeated for both frequencies.
Figure 1b shows the screen of the EPOCH 600 with two reflections on it. The ToF was assessed by the time difference between those two echoes. The choice of the 0.5% difference limit to each measurement was done to ensure greater metrological rigor. That procedure is used to determine the thickness of metallic materials. It is worth mentioning that metals are much more homogeneous than concrete, theoretically having smaller variations between readings performed at the same point.

For the concrete test specimen length, a set of 4 measurements in repetitions conditions was undertaken.

The UPV was defined as the ratio between the length and the ToF, see equation (5).

\[ \text{UPV} = \frac{s}{t} \]  

(5)

in which:
- \( \text{UPV} \) is the ultrasonic pulse velocity \([\text{m s}^{-1}]\);
- \( s \) is the length of the block \([\text{m}]\); and
- \( t \) is the time of flight within the block \([\text{s}]\).

Therefore, since the velocity model depends only on the distance \(s\) traveled and the time of flight \(t\), the velocity model for determining the standard uncertainty combined with the law of uncertainty propagation depends only on two independent variables:

\[ C_{\text{space}} = \frac{\partial \text{UPV}}{\partial s} = \frac{1}{t} \Rightarrow u_{\text{space}} = \frac{u_{\text{comb space}}}{t} \]  

(6)

\[ C_{\text{time}} = \frac{\partial \text{UPV}}{\partial t} = -\frac{s}{t^2} \Rightarrow u_{\text{time}} = -\frac{s}{t^2} \frac{u_{\text{comb time}}}{t^2} \]  

(7)

Combining the uncertainties:

\[ u_{\text{UPV}} = \sqrt{\left(\frac{1}{t} u_{\text{space}}\right)^2 + \left(\frac{s}{t^2} u_{\text{time}}\right)^2} \]  

(8)

in which \( u_{\text{space}} \) and \( u_{\text{time}} \) are the combined standard uncertainties of dimensional and time quantities.

3.3 Compression resistance analysis
Concrete resistance measurement systems are hydraulic presses. When actuated, the presses apply continuous force progressively increased at rates that can be pre-defined or adjustable. The rate of the applied load must be constant and, according to ABNT NBR 573:2018 [16][17], its value
can be between $0.30 \text{ MPa s}^{-1}$ and $0.60 \text{ MPa s}^{-1}$. Charging is interrupted when the instrument identifies a drop in applied force, which indicates a rupture of the specimen.

To carry out the test, it is necessary to align the specimens’ geometric center and the axis of the applied force. After the rupture force is measured, as the area of the base of the specimen is known, it is possible to calculate the pressure for each assay. This procedure allows getting the pressure corresponding to the compressive strength of the concrete ($F_c$), usually expressed in megapascals (MPa).

$$\sigma_c = \frac{F_c}{A}$$  \hspace{1cm} (9)

The area $A$ was constant and defined as $A = \pi r^2 \text{ mm}^2$, in which $r = 50 \text{ mm} (A = 7853 \text{ mm}^2)$.

### 3.3.1 Uncertainty of compression force.

The results obtained were corrected according to information present in the calibration certificate of the equipment. Therefore, for each indicated force ($F_i$) by the equipment, a corrected force ($F_c$) was calculated as:

$$F_c = F_i + (aF_i + b)$$  \hspace{1cm} (10)

In equation (10), $a$ is the slope and $b$ is the intercept of the calibration curve combining the indicated force and its correction informed in the certificate.

For the uncertainty related to the force ($u_{Fc}$), the calibration certificate was also employed to get uncertainties of the readings performed. Then the uncertainty of the corrected force was calculated as:

$$u_{Fc} = F_c c + d$$  \hspace{1cm} (11)

where $c$ is the slope and $d$ is the intercept of the calibration curve formed by the corrected force and the uncertainty declared for each measurement in the certificate.

### 3.3.2 Uncertainty of area.

Its uncertainty was defined as $1\% A$ or $78.5 \text{ mm}^2$. The area uncertainty was arbitrarily defined by the authors for this work.

### 3.3.3 Final uncertainty of compression resistance.

After determining the uncertainties of force and area, the final uncertainty is assessed as follows.

$$u_\sigma = \sqrt{\left(\frac{\partial \sigma_c}{\partial F} u_{Fc}\right)^2 + \left(\frac{\partial \sigma_c}{\partial A} u_A\right)^2} = \sqrt{\left(\frac{u_{Fc}}{A}\right)^2 + \left(\frac{F \times 78.5}{A^2}\right)^2}$$  \hspace{1cm} (12)

### 3.4 Final uncertainty for heterogeneous materials

One of the main problems in the treatment of heterogeneous samples is the definition of a good calculation strategy to establish the resulting uncertainty, which should be representative of the tested sample set. For this research, both velocity and resistance were defined from the average data of each sample, weighted by their respective expanded uncertainties, as follows:

$$M_w = \frac{\sum_i N_i M_i}{\sum_i N_i u_{M_i}^2}$$  \hspace{1cm} (13)
In Equation (13) and (14), $M_w$ is the weighted mean of values $M_i$, $u_w$ is the combined uncertainties $u_{M_i}$ and $DP_M$ is the standard deviation of $M_i$ and $N$ is the number of specimens.

3.5 Normalized error from final results

After calculus of the weighted mean of values it possible to get the normalized error ($E_N$) according to [17] [18]:

$$E_N = \frac{|M_1 - M_2|}{\sqrt{U_{w1}^2 + U_{w2}^2}}$$

(15)

From this approach, it possible to compare if the two results are statistically different or not. When $E_N > 1$, the data can be considered statistically different between them.

4. Results

As shown in Figure 1, UPV varies with the same increasing behavior as the resistance for the two concrete groups analyzed.

Figure 2 shows the values of the measurands and their uncertainties for compressive strength and UPV for groups 1 and 2. Group 1 shows a compressive strength average of 45.9 MPa, while Group 2 shows 65.6 MPa.

As in the study by Philippidis and Aggelis [19], it was observed that UPV increased along with the frequency increased. Besides, these results indicate that the simultaneous use of more than one ultrasonic working frequency can better estimate the correlation between possible UPV compressive strength calibration curves for concrete.

The calculation of the final measurements and uncertainties of each sample group was based on the weighted average of the combined uncertainties according to equations (13) and (14) respectively.

Table 1 presents the results after the calculation of the weighted average values and their respective expanded uncertainties. Compressive strength and UPV for the 54 kHz and 500 kHz frequencies are presented for each sample group and frequency used. Table 2 shows the $E_N$. As can be seen, all normalized errors were greater than unity meaning that these values are statistically different. As mentioned in the methodology (session 3.1), only $E_N$ lower than the unity indicates results statically equivalent. Thus, the results obtained were expected due to the dispersion phenomena where different frequencies provide distinct velocities as can be seen in [19].

| Table 1. Analysis of groups 1 and 2. |
|-------------------------------------|
| Compression resistance | UPVw (54 kHz) | UPVw (500 kHz) |
|------------------------|---------------|----------------|
| $\sigma_w$            | $U_w$         | $U_w$          |
| Group 1                | 45.9          | 1.6            |
|                        | 3784.3        | 54.9           |
|                        | 3931.2        | 75.7           |
| Group 2                | 65.6          | 5.1            |
|                        | 4212.9        | 58.6           |
|                        | 4338.4        | 42.8           |
5. Conclusion
The results obtained using a metrological approach indicated that they can help to improve the quality of the regression curves that relate to the UPV and concrete compressive strength. The typical heterogeneous character of concrete samples is still a challenge as they exert great influence on the results.

It was also observed that velocity variations due to different frequencies can be used as a strategy to better estimate the correlation between compressive strength and ultrasonic pulse velocity in dispersive materials such as concrete. It is observed that the combined use of two or more frequencies may be useful in the best correlation that defines the strength of concrete samples.

As future work, we identified the possibility of investigating the behavior of calibration curves with other physical properties of materials such as static ($E_{\text{stat}}$) and dynamic ($E_{\text{dyn}}$) modulus of elasticity and shear modulus ($G$) [4]. The use of frequency-modulated signals might also be of interest [20].

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Table 2. Normalized error.

| Description                                      | $E_N$ |
|--------------------------------------------------|-------|
| Group 1 in UPV$_{54\,\text{kHz}}$ X UPV$_{500\,\text{kHz}}$ | 1.6   |
| Group 2 in UPV$_{54\,\text{kHz}}$ X UPV$_{500\,\text{kHz}}$ | 1.7   |
| UPV$_{54\,\text{kHz}}$ of Group 1 X UPV$_{54\,\text{kHz}}$ of Group 2 | 5.3   |
| UPV$_{500\,\text{kHz}}$ of Group 1 X UPV$_{500\,\text{kHz}}$ of Group 2 | 4.7   |
| $\sigma_{\text{w}}$ Group 1 X $\sigma_{\text{w}}$ Group 2 | 3.7   |
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