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Strength of Concrete through Ultrasonic Pulse Velocity and Uniaxial Compressive Strength

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Abstract. The noninvasive technique of ultrasonic pulse rate (UPV) is increasingly used in the evaluation of the quality of concrete, providing information about the integrity of structures and preventing possible disasters. Therefore, for its direct application, it is necessary to have a prior correlation between the noninvasive UPV technique and the invasive uniaxial compression resistance (UCS) assay. While correlations have been determined by various authors, each has been given specific conditions and guidelines by the authors because there is no standardized way to perform the correlations. Rather, there are only experimental tests that have generated experimental correlations—both linear and logarithmic—with different graphic shapes. Therefore, this research aims, first, to validate the aforementioned relationship, which allows the compressure resistance of concrete (f'c) to be determined for a given design of concrete mixtures following the American Concrete Institute (ACI. 211.1.). Second, it aims to determine the most accurate trend and the possibly correct form of the correlation plot between the UPV and UCS. In the first instance, 15 plain concrete specimens were designed with an f'c of 28 MPa, whose dosage was carried out following the method of ACI. 211.1. Then, UPV and UCS tests were performed according to regulations in the first 28 days of curing the specimens. Finally, a logarithmic correlation was obtained between the UPV values and the values of the invasive tests for the UCS of concrete. A graphical analysis with some existing correlations of other investigations was then performed, and a similarity in the logarithmic tendency, with a coefficient of determination greater than that of the linear trend, was observed.

Keywords: Concrete structures; Design concrete mixes; Uniaxial compressive strength (UCS); Ultrasonic pulse velocity (UPV); Ultrasound

1. Introduction

Knowing the integrity of concrete structures is important when considering the avoidance or prevention of disasters that may cause loss of life, time, and economic resources. This, added to the exponential growth of the construction sector due to ease of production and the wide use of concrete (Han et al., 2016), has led to a need for structural analysis and monitoring of the mechanical properties of this material, especially the compressive strength of concrete (f'c) —its main property (Sánchez, 2001). This property can be determined using noninvasive and invasive tests, with the noninvasive ones used as complementary tests for concrete (ACI, 2013).

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Among the invasive scanning techniques used to determine the compressive strength of concrete, the most commonly used for the quality evaluation of plain concrete specimens is the uniaxial compressive strength test (Hincapié and Vidal, 2003). This assay has limitations in diagnosing and monitoring the condition of concrete at any age of the structure. Because cylinders are used for the test, the above are made from a concrete mixture with which the structural elements are melted (ASTM, 2019; ICONTEC, 2020). However, although there is a method for extracting the nuclei, which allows a fairly precise determination in real time of the resistance of the element from which they have been extracted, it presents the disadvantage of the necessary repair of the same element (Hincapié and Vidal, 2003; Orozco et al., 2020).

A variety of noninvasive tests can be found in the literature, including ultrasonic pulse velocity (UPV), ultrasonic echo, impact echo, sonic echo, and cross hole sonic logging (ACI, 2013). The UPV method is characterized by its application to evaluate the quality of concrete (Ramadhansyah et al., 2011; ACI, 2013; ASTM, 2016). The noninvasive scanning technique of UPV measurement consists of determining the velocity of an ultrasonic wave that travels through the concrete, estimating the compressive strength of the concrete using correlations (ASTM, 2016; Orozco et al., 2020) without altering the physical or chemical properties of the concrete (Suárez, 2004; Benítez-Herreros, 2011; Salles et al., 2017; Pedreros et al., 2020). These types of waves are acoustic pressure waves with frequencies higher than those of the auditory spectrum of the human ear (Edwin, 2005; Martinez et al., 2007). The UPV technique involves the following two fundamental parts: the generation of ultrasonic waves and the corresponding reception of those waves (Rodriguez et al., 2009; Sharma et al., 2017; Hidayat et al., 2018).

In this sense, previous studies have determined correlations between the noninvasive measurement of UPV and the magnitude of the uniaxial compressive strength (UCS) in plain concrete specimens (Trtnik and Gams, 2015; Sabbağ and Uyanık, 2017). Some have used specific conditions, including Wolfs et al. (2018), with 3D printed concrete for early ages; Hong et al. (2020), with three different concrete mixture designs and nine parameters for 123 plain concrete specimens; Orozco et al. (2020), with a design of concrete mixtures for aggregates and cements from high temperatures, such as the Caribbean region of Colombia; Pedreros et al. (2020), with three conventional mixture designs for six plain concrete specimens; and Troncoso (2012), with concretes made of arid limestone in Ecuador.

However, the studies present variability in the correlation trend as they depend on individual authors, which generates confusion regarding what the most accurate trend and correct form of the graph for this correlation should be. Moreover, ICONTEC (1997) NTC 4325, as a standard method for the application of UPV in Colombia, and ASTM (2016) C597-16 worldwide do not recommend a particular form for the trend and the graph for the correlation between the UPV and UCS.

This article aims, first, to validate the aforementioned relationship that allows the f'c to be determined using the measurement of UPV based on the correlation of UPV and UCS for a given design of concrete mixtures of A.C.I. 211.1. Second, it aims to determine the most correct trend and the possibly correct form of the graph for the correlation between UPV and UCS, increasing the reliability in the application of the noninvasive UPV test and allowing the f'c to be found directly in buildings' structural elements.

2. Methods

The research was proposed taking into account the research carried out in the pilot test (Melo et al., 2020), where three cylindrical specimens of plain concrete with a strength of 3500 PSI or 24.5 MPa were cast. The research methodology is explained in Figure 1.

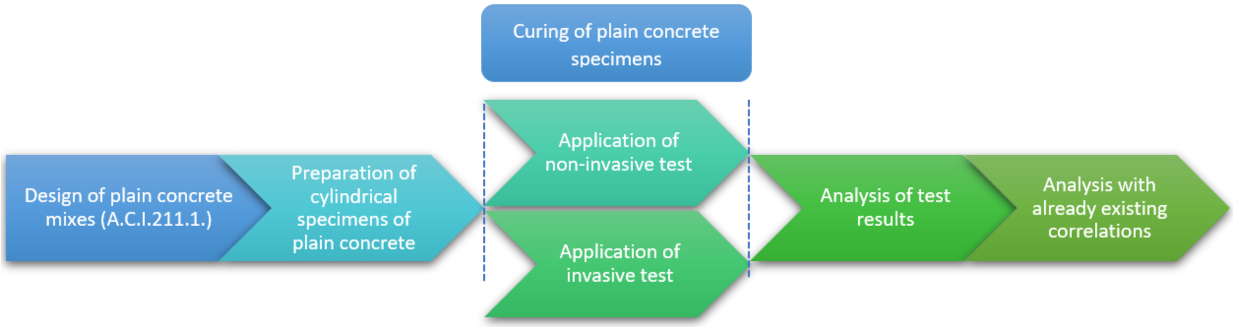


Figure 1 Research methodology

2.1. Design of Concrete Specimens using A.C.I. 211.1. Method

First, the design of the plain concrete specimens for a structural concrete strength of 28 MPa (AIS, 2010) was carried out using the mix design platform following the ACI method (ACI 211.1.), developed by the Structural Health Monitoring Research Hotbed (SIMSE), University Santo Tomás, Colombia. This platform generated the dosage of materials such as cement, aggregates (fine and coarse), and water used to manufacture the plain concrete specimens, taking into account that the application was previously designed according to all the standards of the method (Sánchez, 2001).

At the same time, preliminary laboratories were developed for the physical characterization of the aggregates, such as to determine the particle sizes of the aggregates, ASTM (2014) C136/C136M standard, and the specific gravity and water absorption of the coarse and fine aggregates, ASTM (2015a) C127-15 and ASTM (2015b) C128-15 standards, as shown in Figure 2a. Total evaporable moisture content (Peña et al., 2020), ASTM (2013) C566-13 standard, and the unit mass of both aggregates, ASTM (2017) C29/C29M-17a standard, were also determined, as shown in Figure 2b.

Figure 2 Previous laboratories: (a) Cone of fine aggregate; and (b) unit mass of coarse aggregate

2.2. Manufacture and Curing of Plain Concrete Specimens

The manufacture of the plain concrete specimens was carried out under the standards for the preparation of concrete specimens for laboratory tests ICONTEC (1994) NTC 1377 and ASTM (2007) C192/C192M-07, as shown in Figure 3a, with a minimum of three concrete cylinders manufactured for each test age.

In the manufacturing process, immediately after mixing the concrete, the slump was measured according to the ICONTEC (2018) NTC 396 or ASTM (2015c) C143/C143M-15 standard, as shown in Figure 3b. After 24 hours of casting the cylinders, the molds were removed and placed in water tanks at a temperature of 23°C±2°C for internal curing (Yadav et al., 2018) until the day of the tests (ICONTEC, 1994; ASTM, 2007).

(a) (b)

Figure 3 Manufacture: (a) Concrete mix; and (b) slump of the concrete mix

2.3. Tests Performed on the Concrete Specimens

Next, the methods proposed for the application of the noninvasive UPV tests and invasive UCS tests are presented. Figure 4 shows the curing timeline with the application of the above-mentioned.

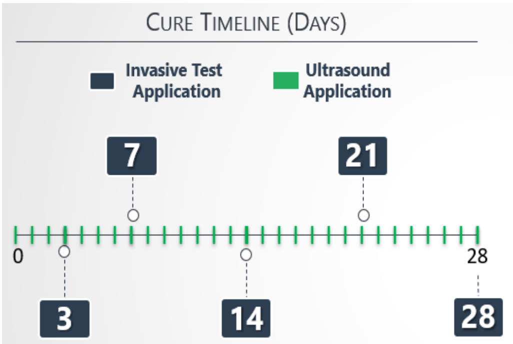
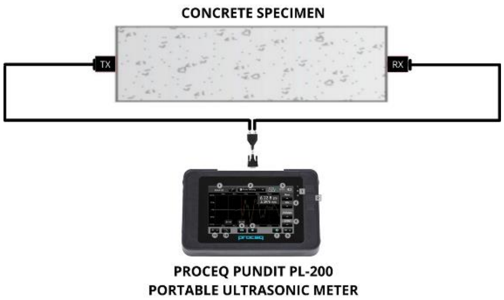


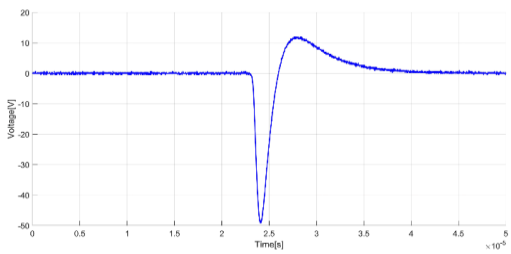
Figure 4 Curing timeline of plain concrete specimens, with the days of application of the noninvasive and invasive tests

2.3.1. Noninvasive UPV test

Figure 5a shows the ultrasonic system used for UPV measurement, which was composed of PROCEQ Pundit PL-200 equipment and two ultrasonic transducers (Tx and Rx) of 54 KHz arranged at the ends of the concrete specimen with acoustic coupling on the contact surfaces. In this case, the equipment generated the ultrasonic pulse shown in Figure 5b to excite the emitter transducer and, at the same time, received the signal obtained by the receiver transducer. Finally, to obtain the UPV, Equation 1 is used, where V refers to the UPV, d to the distance between the transducers or the length of the specimen, and t to the time of flight of the ultrasonic wave.

$$V = d / t \tag{1}$$





(a) (b)

Figure 5 (a) Proposed ultrasonic system for UPV measurement in concrete specimens; (b) electric pulse generated by the PROCEQ equipment for excitation of the Tx emitter transducer

Regarding the data collection for the noninvasive test, measurements were taken using the ultrasonic system shown in Figure 5a, following the parameters of the ASTM (2016) C597-16 standard. Measurements were taken every day for each specimen until the day of failure due to the invasive UCS test. The methodology can be seen in Figure 4 in green.

2.3.2. Invasive UCS test

This test consisted of the uniaxial compression of cylindrical concrete specimens between metal heads placed in a universal compression press, as shown in Figure 6a. The load must be applied at a constant speed between 0.2 and 0.3 MPa/s because the compressive strength of concrete can be affected by changes in speed (ASTM, 2005; ICONTEC 2010). A facing with Sulphur mortar in the cylinders is necessary, as shown in Figure 6b, to ensure the correct stress distribution in the load application of the test (ICONTEC, 1995). Finally, with Equation 2, the *f'c* was determined by dividing the maximum load supported by the specimen *P* in the cross-sectional area *A* and is expressed in MPa (ASTM, 2005; ICONTEC, 2010; Galván-Ceballos and Restrepo, 2016; Damanik et al., 2020).

$$f'c = P / A \tag{2}$$

(a) (b)

Figure 6 (a) Invasive UCS test of cylindrical specimens, (b) cylindrical specimens with sulfur facing

Data collection for the invasive UCS test for the plain concrete specimens was carried out with a universal press ELE INTERNATIONAL, Accu-Tek 350 Series, on days 3, 7, 14, 21, and 28 of the curing time. The methodology can be seen in Figure 4 in dark blue.

3. Results and Discussion

3.1. Design, Manufacture, and Curing

In the development of the research, 15 concrete cylinders were designed, manufactured, and cured. In this way, three cylinders could be failed each day, complying with ICONTEC (1994) NTC 1377 and ASTM (2007) C192/C192M-07 standards. Each cylinder had a structural resistance of 28 MPa, which is the most commonly used residential resistance (Robles and Cárdenas, 2016), and measured 100 mm in diameter by 200 mm in height. Table 1 shows the laboratory data necessary for the development of the ACI. 211.1 mixture design, and Table 2 shows the dosage parameters used in the manufacture of the simple concrete specimens. For the manufacture of the concrete cylinders, the parameters of the ICONTEC (1994) NTC 1377 and ASTM (2007) C192/C192M-07 standards were followed. Similarly, taking into account the ICONTEC (2018) NTC 396 and ASTM (2015c) C143/C143M standards, the slump test was performed at the time the specimens were manufactured, giving a design value of 8 cm. This value is recommended by Sánchez (2001) for walls, scares, beams, and columns with slump of medium consistency.

3.2. Noninvasive Tests Performed

The UPV measurement tests shown in Figure 4 were carried out, providing the results presented in Table 3. In addition, a sample of the signal received by the PROCEQ equipment from the receiver transducer was acquired, as shown in Figure 7a.

Table 1 Data from previous laboratories

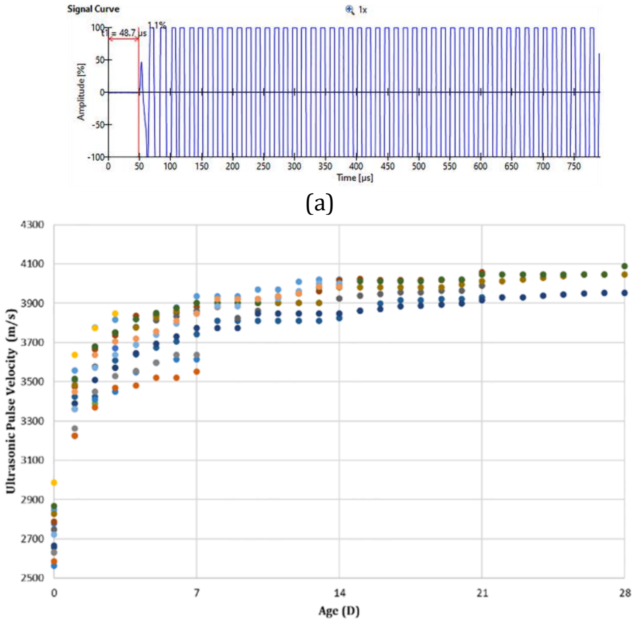
Parameter	Coarse Aggregate	Fine Aggregate	Cement
Apparent density (Kg/m³)	2.0	2.7	-
Density (g/cm³)	-	-	3.0
Compact unit mass	1667	1779	-
Loose unit mass	1530	1566	-
Absorption	1.3	8.7	-
Natural humidity	1.0	9.9	-
Nominal maximum size	1/2	-	-
Fineness module	-	3.1	-

Table 2 Dosage used for the creation of plain concrete specimens

Parameter	Value (Kg/m³)
Mix Design	
Water content	210
Cement content	466
Coarse aggregate content	790
Fine aggregate content	606

In this figure, the measurement of the flight time of the ultrasonic wave through the concrete can be observed.

Figure 7b shows the UPV according to the curing time of the specimens. As can be seen in the figure, the velocity increased rapidly in the first three days, increased slowly until 14 days, and maintained a very slow increasing trend until 28 days. However, it should be clarified that it was not necessary to perform a temperature correction to the UPV results as the temperature was between the acceptable ranges of 10°C and 30°C (BSI, 2004). Table 3 shows the average UPV values of all existing specimens on the day the noninvasive technique was applied versus the results of the invasive technique for the failed specimens on the same day.



(a)

(b)

Figure 7 (a) Signal received by the PROCEQ equipment from the receiver transducer Rx; (b) UPV application data

Table 3 Results of noninvasive tests performed versus invasive tests performed according to day

Age (D)	UPV Average (m/s)	Compressive Strength Average (MPa)
3	3656.80	13.94
7	3790.64	17.69
14	3954.78	23.43
21	3991.16	26.25
28	4028.75	30.94

3.3. Invasive Tests Performed

The UCS tests proposed in Figure 4 were performed, with the results presented in Table 3. The average percentage of compressive strength in relation to the design strength of 28 MPa is shown in Table 4. The compressive strengths were within the acceptable strength ranges for three individual cylinders (ICONTEC, 2010). Figure 8 shows the compressive strength of the specimens according to the day of failure.

Table 4 Compressive strength percentages in relation to 28 MPa

Age (D)	% Compressive Strength (28 MPa)
3	49.78%
7	63.19%
14	83.67%
21	93.75%
28	110.51%

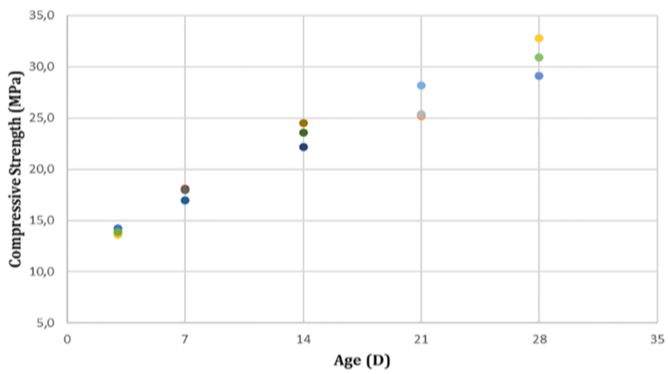
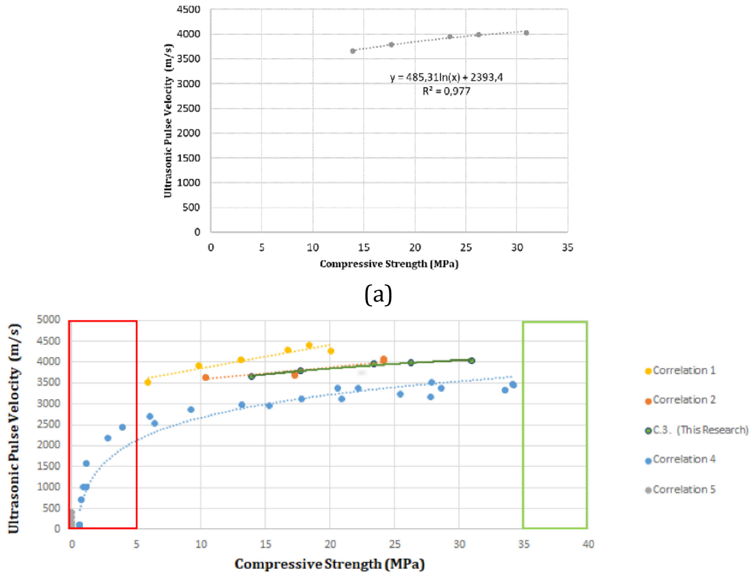


Figure 8 Uniaxial invasive test application data

3.4. Correlation and Discussion

From the data obtained in the research, it was proposed that a correlation be estimated between the values of the noninvasive UPV test from the averages of days 3, 7, 14, 21, and 28 and the average values obtained from the invasive UCS test on the same days, as shown in Table 3. In Figure 9a, it can be seen that the correlation presents a logarithmic trend, whose equation is given in Equation 3, with a coefficient of determination of 0.977, which, being considerably close to the unit, indicates a good fit (Gea et al., 2014).

A graphical analysis of the correlation previously estimated with different correlations found in the literature was also performed, plotted using data from the noninvasive UPV test and the invasive UCS test of concrete found in the respective scientific articles. Correlation 1 corresponds to the research of Orozco et al. (2020), correlation 2 to the research of Pedreros et al. (2020), and correlation 3 to the present research, all of which present data for some of the days 1, 3, 7, 14, 21, and 28, as well as a correlation with a linear trend, except for the present one, which is logarithmic. Correlation 4, however, corresponds to the research of Hong et al. (2020), which presents data for 16, 20, 24, 48, 48, 72, 120, 120, 168, 360, and 672 hours or 28 days, as well as a correlation with a logarithmic trend. Finally, correlation 5 corresponds to the research of Wolfs et al. (2018), which presents data for 5, 15, 30, 30, 60, and 90 minutes, in addition to a correlation with a linear trend. The correlations mentioned above are shown in Figure 9b. The previous correlations were selected because each one presents specific conditions, thus showing possible similarities among the numerous correlations that can be found in the literature.



(b)

Figure 9 (a) Logarithmic correlation between the value of the noninvasive UPV test and the invasive UCS test of concrete; (b) graphical correlations of the five research studies

$$y = 485.31\, ln(x) + 2393.4 \quad (3)$$

where x is the concrete compressive strength (MPa), y is the UPV (m/s)

With the data of the previously mentioned graphic correlations, a conversion from linear to logarithmic trend was made for correlations 1, 2, and 5, generating the possibility of carrying out a logarithmic regression to each one of these, as well as to correlation 3, as shown in Figure 10.

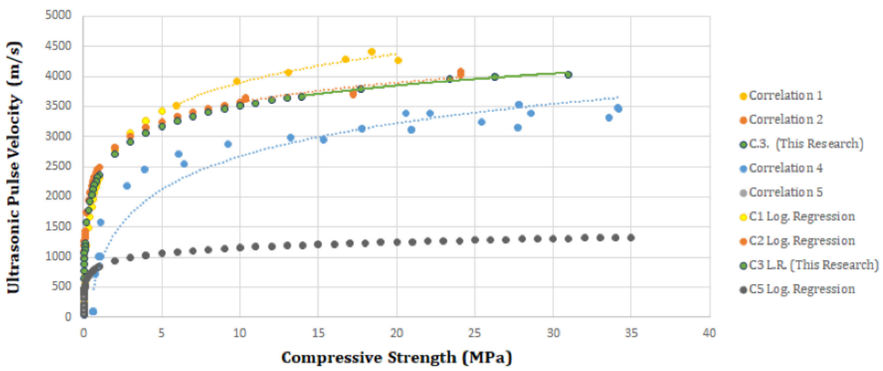


Figure 10 Logarithmic regressions of the graphical correlations

In Figures 9b and 10, it is possible to observe that a correlation with a logarithmic trend can be used to approximate the existing relationship between the UPV and compressive strength of concrete, as seen with correlation 4, using research by Hong et al. (2020). However, if linear regressions were performed at correlations 1, 2, and 3, they would have an initial ultrasonic pulse rate greater than 3000 m/s, and correlation 4 would not reach a compressive strength of 5 MPa, which would contrast with the correlation of Hong et al. (2020). Also, the coefficient of determination of the trend line of correlation 3, drawn from the current research, is closer to the unit in this form, as shown in Table 5. In contrast, although correlations 1, 2, and 5 appear to have a linear trend, they only correspond to an interval on the graph, if complete. Likewise, from Figure 10, it can be observed that when performing the logarithmic regression, correlations 1, 2, and 3 (though not correlation 5) present similarities with correlation 4, possibly generated by the scale of the invasive test data, which are of the order of KPa. A point of discussion is the lag in the correlations, possibly produced by the difference between the ultrasonic meters and the uniaxial compression presses used in each of the studies.

Table 5 Equation and coefficient of determination of trend lines

	Trend Line	
	Linear	Log.
Correlation 3 (This research)	$y = 22.869x + 3378.2$ $R^2 = 0.951$	$y = 485.31\ln(x) + 2393.4$ $R^2 = 0.977$

4. Conclusions

The results shown in Figures 7b and 8 indicate that during the 28 days of the concrete curing, the UPV and the compressive strength of the concrete increase as the days pass. Therefore, this study proposes a correlation with a logarithmic trend that can be used to approximate the relationship between the UPV and the compressive strength of concrete, which would be useful to implement in devices used to measure the UPV in concrete.

For future research, it is recommended that a correlation be performed involving the application of the noninvasive and invasive tests in the first 24 hours (red section of Figure 9b) and in the interval after 28 days of curing of the concrete specimens (green section of Figure 9b), with the objective of obtaining a more complete picture in those intervals of the graph.

Considering the comparison of Figures 9 and 10, it is suggested that the appropriate form of the correlation graph between the noninvasive UPV test and the invasive UCS test is a logarithmic trend. However, future researchers should consider comparing the correlations in the missing intervals shown in the green and red sections of Figure 9b.

The results obtained in this research demonstrate that the noninvasive UPV test can be established as a reliable way in the in situ estimation of the quality of concrete, thus allowing the f'c of concrete to be determined directly in the structural elements of buildings and avoiding the application of invasive tests that alter the physical or chemical properties of concrete.

Acknowledgements

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