

Original Article

Forensic Structural Engineering: A Comparison of Non-Destructive and Destructive Methods for Assessing Concrete Quality in Columns within the Peruvian High-Andean Zone

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Abstract - In the high-andean zone of Peru, the concrete structures are exposed to adverse conditions that can affect its durability and resistance, due to the fact that they tend to deteriorate over time; therefore, it is necessary to periodically perform a quality evaluation of the material with the purpose to guarantee the safety in the service requests. Nevertheless, to perform this characterization of the material continues to be a structural challenge because of the lack of clear correlation between destructive and non-destructive methods applied in diverse structural elements. Given this, this research has the objective to execute the comparison between the destructive and the most conventional non-destructive test as alternatives for the evaluation of concrete quality. For attaining this purpose, this study analyzed mainly the concrete column elements utilizing the rebound hammer test according to ASTM C805/C805M, the ultrasonic pulse velocity test according to ASTM C597, and concrete core extraction according to ASTM C42/C42M, followed by compressive strength testing according to ASTM C39/C39M, comparing the obtained results for analyzing its correlation degree and its applicability. The findings demonstrate that when employing the corresponding variable to the ultrasonic speed and the rebound index independently in the correlation with the diamond cores its provides a variation margin of around $\pm 2.95\%$ and $\pm 3.62\%$ respectively, for the prediction of the compressive strength of the material. However, to opt for these approaches involves an uncertainty rate higher than the SonReb model, this is the main reason why the implication of selecting a testing methodology was carried out, resulting the SonReb model the most outstanding for the estimation of the compressive strength in constructions with technical precedents.

Keywords - Forensic structural engineering, Non-destructive and destructive testing, High-andes concrete columns, In-situ compressive strength evaluation, Cold climate concrete degradation.

1. Introduction

From the 20th century, reinforced concrete has been employed for the construction of infrastructure because of its resistances and durability [1]. Likewise, it remains to be the most efficient and cost effective construction medium [2]. The quality evaluation of the concrete is a fundamental practice that is most relevant and has gained more interest in recent years, which permits to maintain the integrity safety in the structures or buildings of industrial or civil nature [3] because it is common for this material to suffer degradation by deterioration factors like the constant climate exposition, freeze and thaw cycles, erosion, crystallization, leaching, overloading and others [1, 4] This situation creates the necessity to improve the live expectancy of an existing building [1]. It is necessary to evaluate numerous concrete parameters like compressive strength, elasticity modulus, corrosion probability, carbonation, homogeneity, and other

possible changes through the time [5]. Besides, in regions that are prone to seismic activity, the existing buildings face considerable risks due to the presence of vintage constructions that were designed without considering anti-seismic standards. For instance, in Italy, more than the 60% of the existing buildings are exposed to seismic risk [6].

In this context, forensic structural engineering plays a key role because it investigates the causes of structural failures in buildings and infrastructures, employing engineering principles, detailed analysis and event reconstruction for determine why a structure failed or got deteriorated [7]. The evolution technology has boosted, significantly, the development of evaluation tests to concrete structures that permit to know their durability and resistance with more precision and speed because a precise evaluation of the current mechanical properties of the material is essential for



guaranteeing a reliable numerical prediction of its behavior [8]. These progresses include the adoption of ultrasonic techniques, Sonic, and superficial wave analysis that are now essential for the evaluation of big structures like bridges and presses [9]. There are two approaches to determine and estimate the compressive strength of concrete: non-destructive and destructive tests, the destructive tests are executed by crushing and destroying the sample, and non-destructive tests are the ones that do not infringe, in any case, the integrity of the tested structure [10]. On the other hand, semidestructive tests also exist, and they require to take material samples or any other minor fraction of the structure integrity [4]. Non-destructive tests determine the quality and integrity of the materials or components in response to the prevention necessity and structural damage detection without affecting its capacity to perform its functions [11]. For instance, the sclerometric non-destructive approaches can determine the durability, homogeneity, and compressive strength of the concrete structure incorporated into structural elements [4]. This method is also useful for evaluating structures after a fire [12]. The evaluation of the concrete resistance in existing structures through non-destructive methods represents a significant and complex challenge. Although many studies and researches were performed for developing tools and models that permit the execution of a test, there is not a fully validated approach yet that ensures the quality and efficacy of the process [13].

The use of empirical correlative tests under different conditions can provide accurate or incorrect data. This may occur due to the handling or use of equipment that is not suitable for the test, poor equipment handling, or environmental factors. This is even more important when concrete mixtures are evaluated, since concrete is one of the main materials in civil works. The relationship between standard compressive strength and the ultrasonic technique for concrete cylinders can be used as a fitting line to predict concrete strength. The wave velocity can be as useful as the standard test method [14]. However, this interaction between tests needs to be calibrated with destructive results, considering the natural dispersion of the element [8].

An important limitation in concrete mix design in high-altitude areas is related to exposure conditions. This limitation becomes especially important in high-altitude environments, where exposure conditions can modify the properties of the surface layers of concrete.

Exposure to low temperatures may significantly delay the hydration of cement and the development of its strength. In frosting conditions, the freezing of the water mixture may affect even more the development of the microstructure and the mechanical performance of the concrete [15]. These effects are particularly relevant in high-altitude cold environments, where other exposure conditions may influence the concrete's properties [16].

In high Andean areas, some studies show a rapid decrease in moisture under low atmospheric pressure. This behavior alters the heat of hydration, the densification of the microstructure, and the mechanical properties of the exposed surface [16]. In the Peruvian context, this situation can be observed more frequently because there are areas located above 4000 m.a.s.l. These conditions directly affect the execution of a proper construction process and the quality of the results obtained.

Recent studies show that the reliability of non-destructive methods to estimate the compressive strength of concrete considerably depends on the calibration procedures performed and the characteristics of the assessed concrete. Mata et al. [8] highlighted that the relationship between the velocity of the ultrasound pulse and the compressive strength must consider the dispersion of the on-site measurements, instead of solely considering general empirical correlations. Likewise, Gunes et al. [17] informed that the combination of different non-destructive indicators may improve the predictions of the concrete's strength in comparison to the isolated use of individual measurements. Angiulli et al. [18] Also demonstrated that the SonReb conversion models calls for calibrations with data gathered from destructive trials to evidence the uncertainty and non-linear behavior. Recent models that are locally calibrated and combine measurements with rebound hammers and ultrasound pulse velocity have reported determination coefficients that are close to $R^2=0.79$, which supports the relevance of developing correlations for the materials and specific trial conditions under study [19]. Regardless, these approaches did not specifically encompass reinforced concrete columns that were assessed in High-Andean environmental conditions, considered in the present study.

This research considered core extraction and rebound hammer testing. To obtain a better view of the tests carried out, ultrasonic pulse velocity, rebound index, and strength obtained from concrete cores were incorporated simultaneously within a combined SonReb calibration [17]. Therefore, the research gap is focused on the validation of the three methods used in the inspection of reinforced concrete columns under cold, high-Andean conditions in Peru. It is known that areas located above 3000 m.a.s.l. can affect both proper data collection and the correct execution of the construction process or concrete placement in columns. Workers must not only deal with the effects of altitude, but also with the surrounding environment and the topography of the site. All these factors can increase uncertainty in the measurements or indirect estimates of concrete strength.

Based on this gap, the objective of the research is to compare the performance of diamond core extraction as a destructive method with ultrasonic pulse velocity and rebound index as non-destructive methods to evaluate the compressive strength of concrete columns under high-Andean conditions in

Huancayo, Peru. The results obtained will help to answer the hypothesis, which is based on the integration of both non-destructive variables through a calibrated SonReb model. With the results obtained from the cores, it will be possible to verify the relationship between the tests and reduce the error presented when each method is used individually.

Therefore, the main contribution of this study is the local calibration and comparative assessment of destructive and non-destructive methods applied to reinforced concrete columns in High-Andean environmental conditions. The novelty of this study resides in assessing the velocity of the ultrasound pulse and the rebound index, both independently and through a SonReb combined model, using the compressive strength obtained from concrete samples extracted from the structures as reference, under the same on-site conditions. This approach enables to quantify the reduction of the prediction error by means of combining the

two non-destructive variables and provides a locally calibrated relationship for the assessment of the concrete's strength in the assessed structures.

2. Materials and Methods

2.1. Procedures for Concrete Columns Evaluation

Figure 1 shows a flux diagram framework to evaluate the integrity of concrete columns. The column is identified and marked, then its surface is cleaned and polished for its preparation. Consequently, an ultrasonic pulse test is performed to evaluate the internal homogeneity of the column. Then, specific regions are marked for additional testing. The aforementioned regions are measured with a sclerometer to evaluate surface hardness. Later, the diamond core test is performed to obtain reference samples for compressive strength evaluation. Finally, the obtained results are gathered and compared.

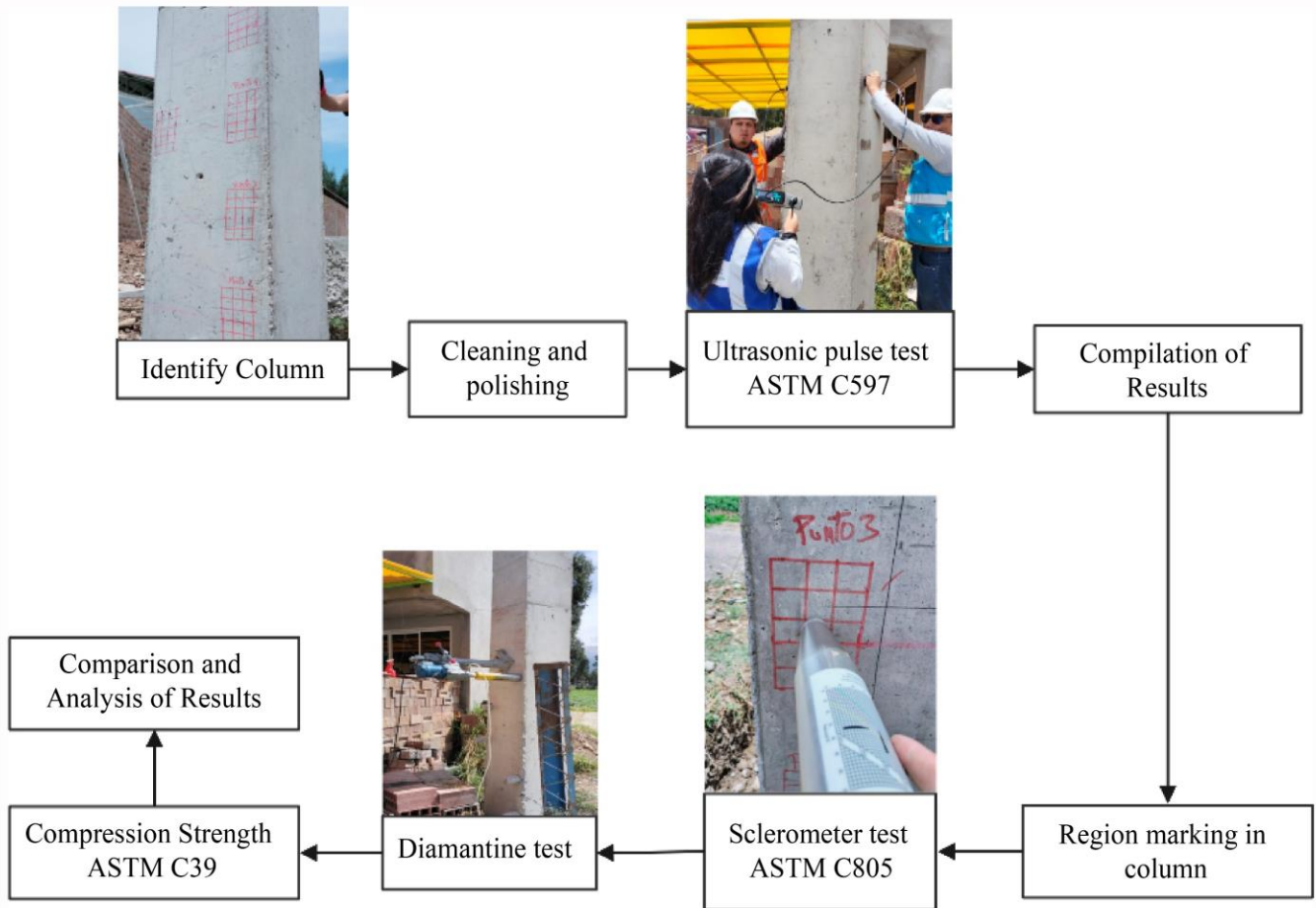


Fig. 1 Procedure for concrete columns evaluation

In the present investigation, the study sample is located in Huancayo, approximately 150Km south from the city of Junin. Said location has often rainy weather, at an altitude of 3249 meters above sea level. Considering the local context,

several trials were performed to guarantee the resistance and durability to ensure applicability and performance, considering the abovementioned environment.

For the evaluation, the strategy was based on the use of four reinforced concrete columns identified as CI 01, CE 01, CI 02, and CE 02. Columns CI 01 and CI 02 corresponded to elements located under indoor conditions, while CE 01 and CE 02 corresponded to elements exposed to outdoor conditions. These columns were differentiated by their sections: internal columns had dimensions of 30×30 cm, and external columns had dimensions of 25×30 cm. In both cases, a standard compressive strength of $f'_c = 21$ MPa was used, which is commonly applied in structural concrete columns. The control points were located from P01 to P06, obtaining a total of 24 evaluation positions. For each zone, non-destructive trials were performed, using the rebound hammer and ultrasound pulse velocity methods, in compliance with the ASTM C805/C805M and ASTM C597 norms, respectively,

[20, 21]. Consequently, concrete samples were taken and subjected to compression trials. The compressive strength gathered from the extracted concrete samples was used as a direct reference to calibrate and assess the two non-destructive measurements. Therefore, the use of a destructive reference in comparison to two methods of Non-Destructive Trials (NDT) does not represent a disequilibrium in the experimental design, since the UPV and the rebound index provide indirect estimation of the status and the strength of the concrete, whereas the compressive trial of the sample provides the referential strength, used for the comparison and the calibration of the model. All of the measurements were performed in comparable on-site conditions to maintain the consistency between the destructive and non-destructive assessments.

Table 1. Sampling plan for concrete column evaluation

Element	Exposure condition	Section (cm)	Design f'_c	Control points	Rebound hammer measurements per point	UPV per point	Core sample
CI 01	Interior	30×30	21 MPa	6	15	1	$\varnothing 100 \times 180$ mm
CE 01	Exterior	25×30	21 MPa	6	15	1	$\varnothing 100 \times 180$ mm
CI 02	Interior	30×30	21 MPa	6	15	1	$\varnothing 100 \times 180$ mm
CE 02	Exterior	25×30	21 MPa	6	15	1	$\varnothing 100 \times 180$ mm

The evaluation of the columns was carried out randomly, without sufficient technical documentation to determine their strength in relation to the year of construction. This condition may lead to inaccurate data.

However, according to standard criteria, concrete should reach its design strength after 28 days. The age of the concrete was not included as a quantitative variable in the correlation models, and this condition was considered as one of the limitations of the study.

2.2. Methods

2.2.1. Sclerometry Test

According to the NTP 339.181 [22], this non-destructive approach measures the uniformity hardened concrete through the number of bounces obtained through a hammer that is actioned by a spring, as it is pictured in Figure 2(a), correlating the resistance of the concrete according to the ASTM C805/C805M norm. The area test must have at least 150 mm or 6 inches of diameter, must be clean and polished if needed. The hammer is held perpendicular to the Surface in order to perform the impacts, recording each rebound and discarding values with more than 6 units from the average [20]. For better performance of the rebound hammer tests on

the columns, the surface of the section had to be cleaned by removing agglomerated concrete or mortar coating, such as plaster. The test had to be carried out on the original surface of the column in order to obtain suitable data.

For the test, the corresponding impacts were applied as required by the standard. A grid with a spacing of 25 mm was prepared, where 15 impacts were made. The rebound hammer was used in a position perpendicular to the sample, in this case, the column. In these readings, values that were far from the obtained measurements had to be selected or discarded according to the standard.

ASTM C805/C805M establishes that the rebound number can be used to evaluate the uniformity of concrete and to estimate strength only when an appropriate relationship with in-place strength is developed. Surface and exposure conditions of the element must also be considered [20]. 15 measurements were performed through the usage of a sclerometer in a grid drawn over the concrete Surface as shown in Figure 2(b). Each impact was applied with a minimum separation of 2.5 cm or 1 inch with the aim to avoid interferences among measurements, guaranteeing a uniform distribution in the evaluated area.

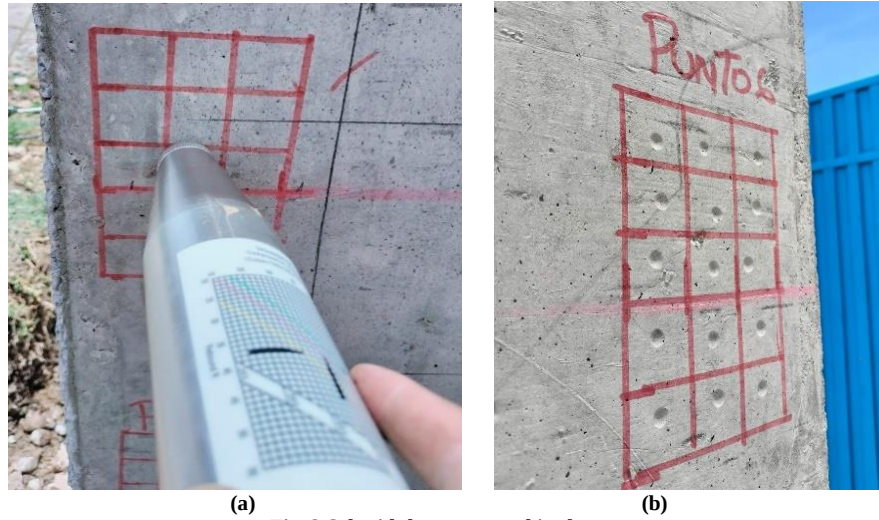


Fig. 2 Schmidt hammer used in the test

For calculating the compressive strength, each average value of the rebound was placed on the X axis, and with the application angle, the expected compressive strength can be calculated with a dispersion margin error as shown in Figure 3.

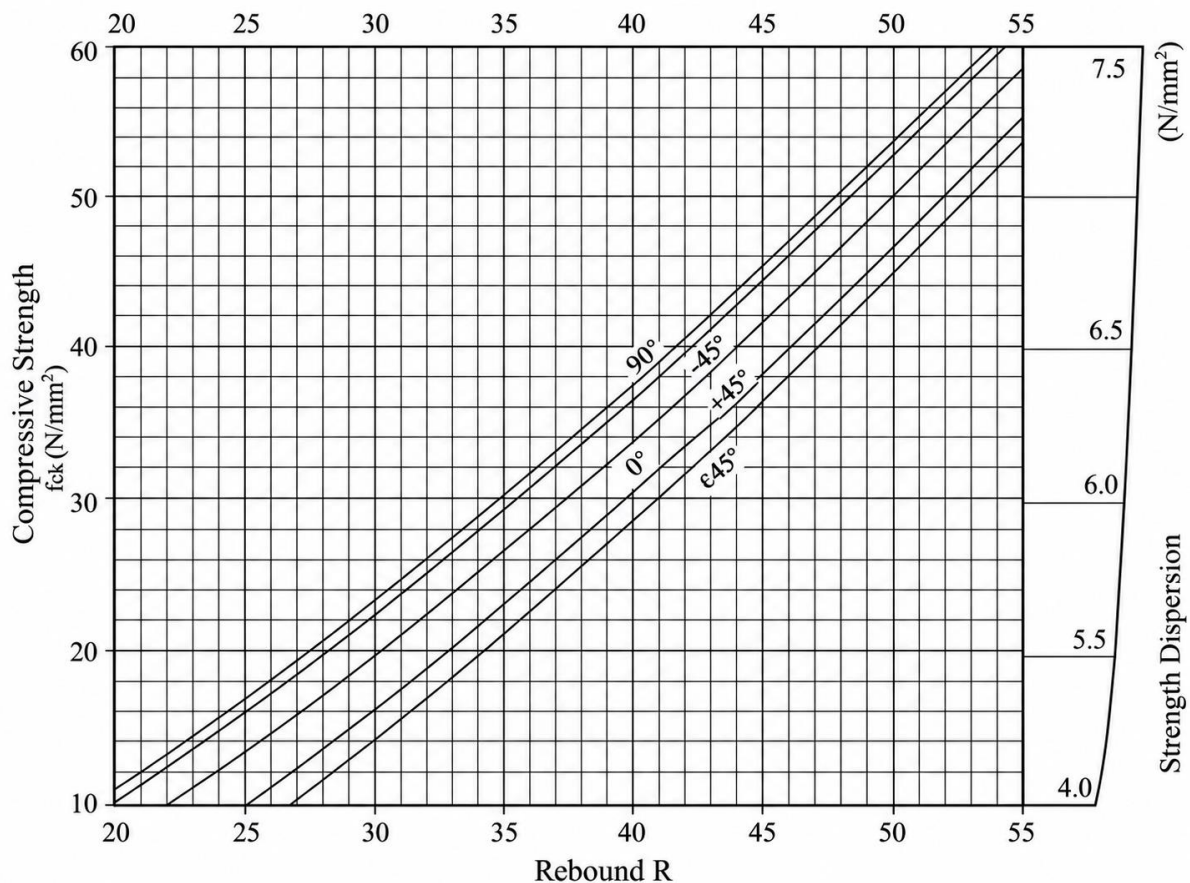


Fig. 3 Nomogram used in the sclerometer test

2.2.2. Ultrasonic Pulse Velocity Test

The test, regulated by ASTM C597-22 [21], measures the uniformity of the concrete through the propagation velocity of longitudinal waves. Using a pulse generator, transducers (20-

100 kHz), and a time meter (precision of 0.1 μ s) and a coupling agent as represented in the scheme in Figure 4(a). The application was performed in columns as shown in Figure 4(b).

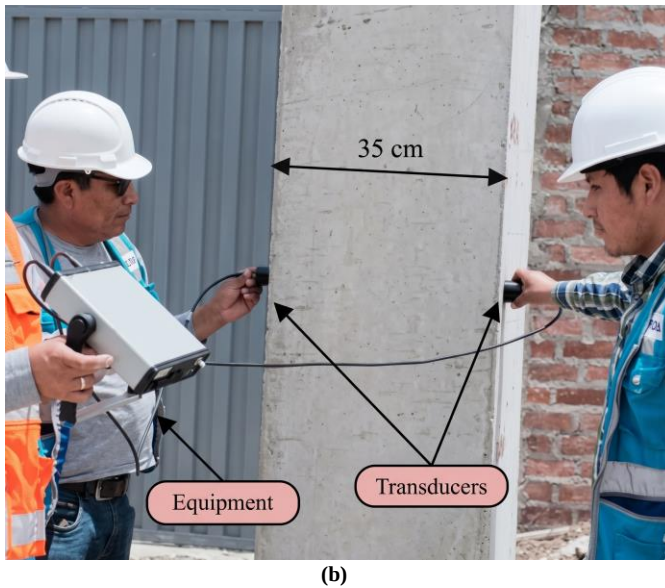
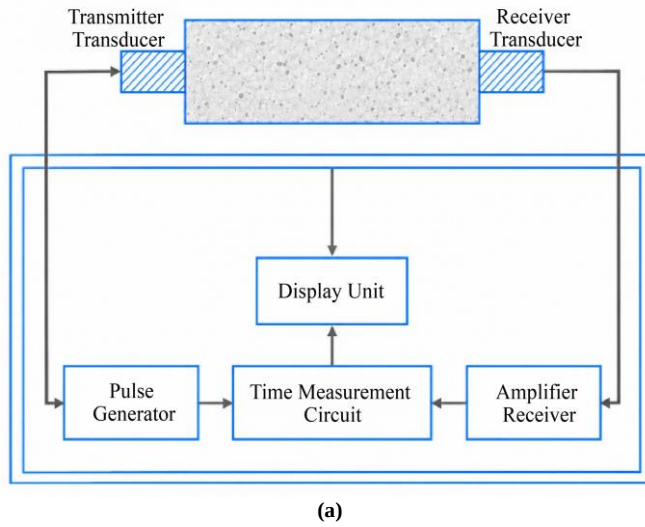


Fig. 4 Ultrasonic pulse velocity test schematic

ASTM C597 [21] determines the propagation velocity of ultrasonic compression waves through concrete. This test is used to verify the uniformity and integrity of concrete, as well as to estimate crack depth and evaluate changes in structural properties over time. To obtain suitable data, as required by the standard, the equipment must be calibrated using a reference bar with a known time value. A coupling agent must be added to reduce discontinuities between the transducers and the concrete surface. In each sampling point, the path length L between the transducers was determined and the transit time T was recorded. Then, the ultrasonic velocity was calculated as $V = L/T$. ASTM C597 [21] establishes that the reliability of the measurement depends on the precise determination of the path length and transit time. It also indicates that moisture conditions and the presence of reinforcing steel can influence the measured velocity. Therefore, data collection was supervised under the same experimental procedure.

The velocity pulse was calculated through the Equation 1:

$$V = \frac{L}{T} \quad (1)$$

The norm ASTM C597 established that the obtained velocity (in m/s) is directly linked to the density, the dynamic modulus of elasticity and the dynamic modulus of Poisson for them hardened concrete [21]. These parameters can be determines by employing the Equation 2.

$$V = \sqrt{\frac{E*(1-\mu)}{p*(1+\mu)*(1-2\mu)}} \quad (2)$$

Where:

E : Elasticity modulus
 μ : Poisson modulus

The classification of the quality of the concrete, according to [21], is related with the ultrasonic pulse speed, which are contemplated on the following Table 1.

Table 2. Pulse velocity classification

Concrete Quality	Ultrasonic Pulse Velocity (m/s)
Excellent	> 4570
Good	From 3650 to 4570
Regular	From 3050 to 3650
Poor	From 2130 to 3050
Very Poor	< 2130

2.2.3. Diamond Core Test

The diamond core drilling test evaluates the properties of the hardened concrete, like the compressive strength, traction and flexure, being ideal for verifying the quality of the concrete or analyzing old structures. Cylinders are extracted using diamond-tipped drills of at least 94 mm of diameter. For this, it is necessary to determine the ratio between the length dimensions and the diameter as shown in Equation 3.

$$\frac{L}{D} ratio = \frac{L}{D} \quad (3)$$

Where:

L/D ratio: Ratio between length and diameter
 L : Length
 D : Diameter

If the ratio between the length and the diameter is superior to the value of 1.75, then the application of the correction factors it is not necessary. Otherwise, the correction factors according to the norm NTP 339.034 [23] that is depicted in Table 2.

The outcomes permit to diagnose defects and verify standards as the ACI 318, that required an average resistance of at least 85% of the already specified.

Table 3. Core drilling test correction factor

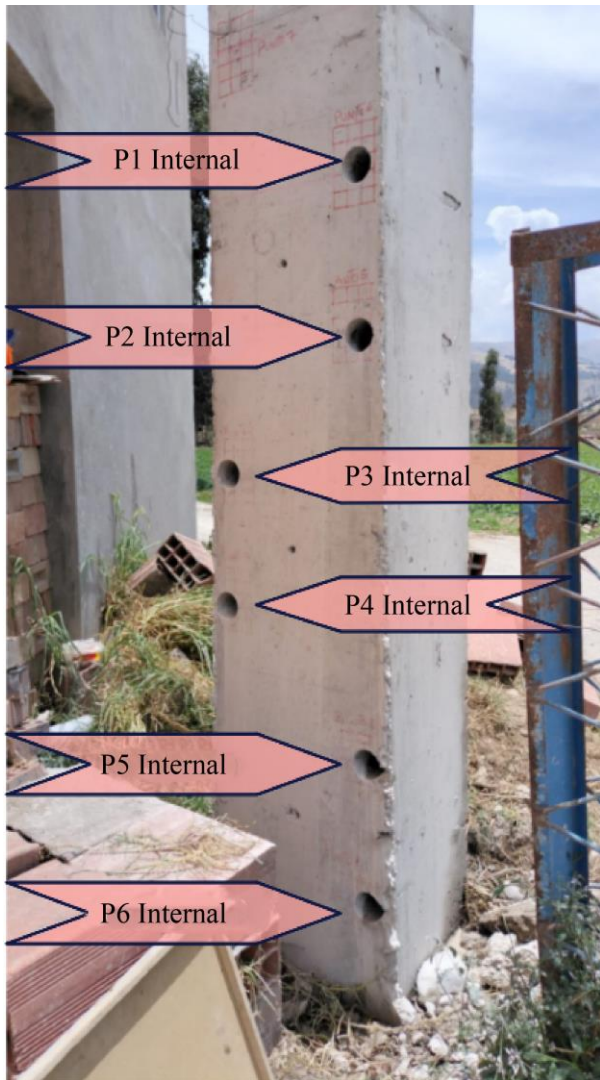
L/D Ratio	Correction Factor
1.75	0.98
1.50	0.96
1.25	0.93
1.00	0.87

The tests were applied in the four columns, from the internal column views (CI 01) and the external column (CE 01), as shown in Figure 5(a) and 5(b) respectively. In the same way, these application were perform in the internal column view (CE 02) that is exhibited in Figure 5(c) and 5(d). In all the columns, the 6 tests were executed in each one; for the diamond core test, samples of 4" (100 mm) of diameter and 7" (180 mm) of length were taken. Thus, the L/D ration is 1.8 with a correction factor of 1.00. The diamond core test was carried out after obtaining the rebound hammer and ultrasonic

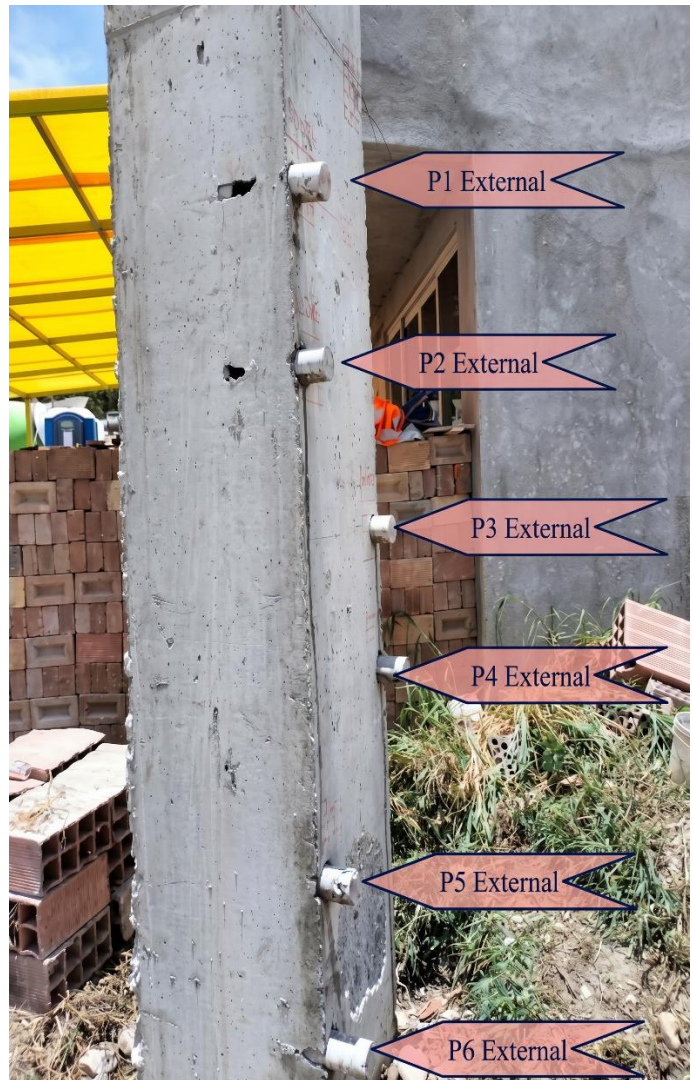
test results through an indirect relationship with reference strengths. After this, core samples were extracted using diamond drilling equipment. The cores had a diameter of 100 mm and a length of 180 mm, obtaining an L/D ratio of 1.8.

ASTM C42/C42M [24] establishes the conditions that each sample or core must meet. These include the location of the core within the element, its orientation, moisture condition, and length-to-diameter ratio, since these factors can affect the measured strength. After obtaining representative samples, as described in ASTM C42/C42M, each core sample was subjected to axial compressive loading. Based on these results, a final comparison with the non-destructive tests was carried out [25].

The dimensions of the internal columns of 30 x 30 cm, and the external columns are 25 x 30 with a design of $f'_c = 210 \text{ kg/cm}^2$.



(a)



(b)

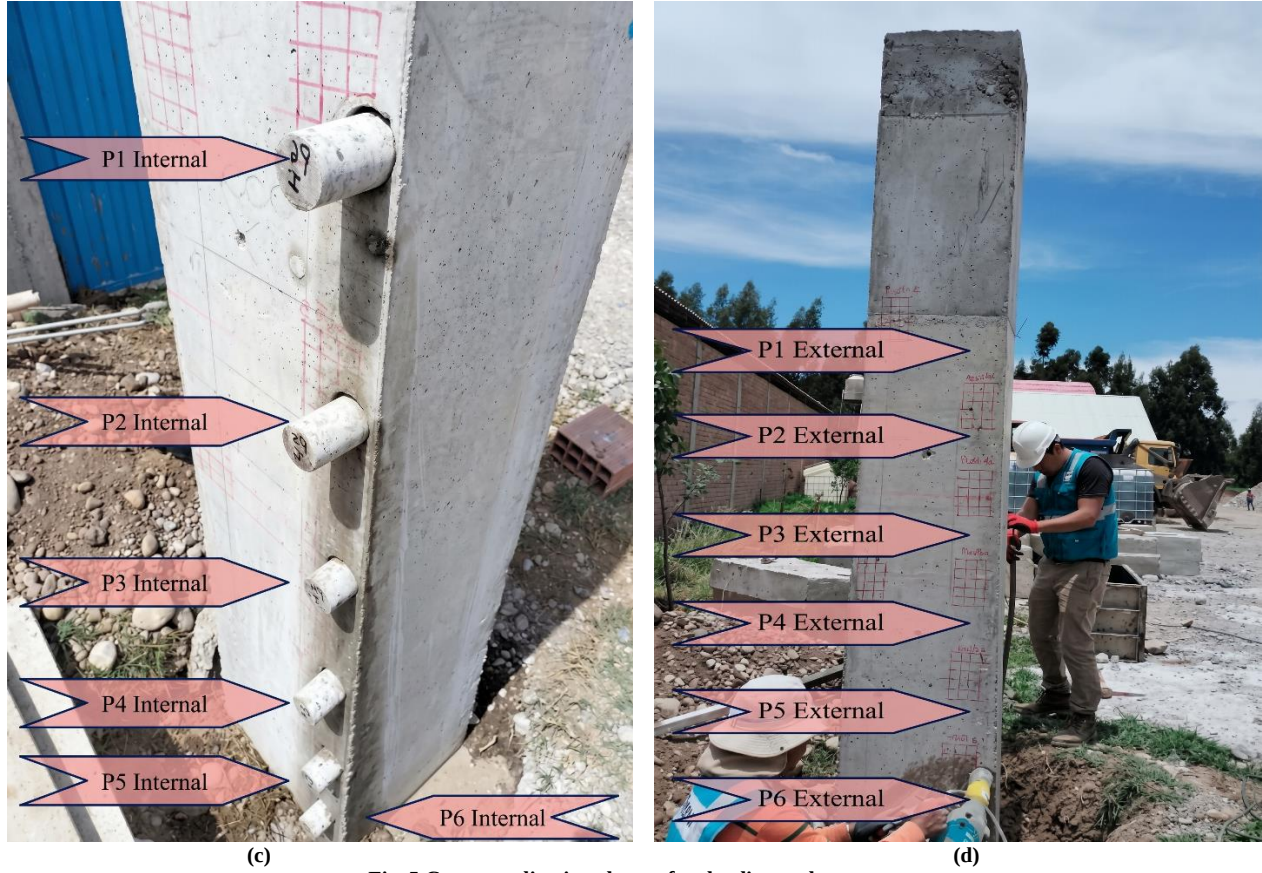


Fig. 5 Core sampling in columns for the diamond core test.

2.2.4. Compression Test

After the diamond core test, the compression test was executed, in accordance with the norm NTP 339.034 [23] and the ASTM C39/C39M. This procedure consists of applying an axial load over extracted cylinders until reaching their failure point [25].

The test is executed utilizing a hydraulic press of compression, calibrated and certified, capable of applying uniform and controlled loads in a fixed rate. The press must have smooth, and aligned loads, guaranteeing a uniform distribution of the pressure in all of the sample surface. For determining the compressive strength, the Equation 4 is calculated.

$$R_c = \frac{C}{A} \quad (4)$$

Where:

- R_c: Compressive Resistance (MPa)
- C: Applied Load (N)
- A: Area (mm²)

Statistical Analysis

According to [26], statistical analysis makes it possible to establish reliable correlation models between compressive strength and the physical variables of concrete. It also helps to

determine the significance of mechanical changes through analysis of variance (ANOVA) and confidence intervals. In this research, the analysis was carried out using the compressive strength obtained from the diamond core samples, *f*'_c (MPa), as the dependent variable. The initial inspection variables were ultrasonic pulse velocity, UPV (m/s), and the rebound index, RI, obtained from the rebound hammer test. The first statistical tests were carried out using descriptive statistics, including the mean, standard deviation, variance, minimum and maximum values, and coefficient of variation [27]. These data helped to characterize the dispersion of the measurements. Then, regression models were applied to the non-destructive test results based on their relationship with concrete strength. These models were complemented with the combined SonReb model, for which a multiple linear regression was used, as shown in Equation 5:

$$f'_c = \beta_0 + \beta_1 * (VPV) + \beta_2 * (IR) + \varepsilon \quad (5)$$

Where:

- f*'_c: Estimated compressive strength of concrete (kg/cm² or MPa).
- β₀: Intercept or constant of the model.
- β₁: Regression coefficient for ultrasonic pulse velocity.
- UPV: Ultrasonic Pulse Velocity (m/s or km/s).
- β₂: Regression coefficient for the rebound index.

RI: Rebound or sclerometric index, dimensionless.

ε : Random error or residual term.

For the evaluation of the regression model through ANOVA, a significance level of $\alpha = 0.05$ was considered) [28]. This parameter was complemented with the analysis of the Coefficient of Determination (R^2), the adjusted coefficient of determination (R^2_{adj}), the Mean Absolute Error (MAE), the Root Mean Square Error (RMSE), and the Mean Absolute Percentage Error (MAPE) [29].

The use of these steps helps to provide more reliable and accurate data for the evaluation and understanding of the research [18]. This is consistent with ACI 228.1R-19, which considers the relationship between in situ tests and concrete strength prediction through statistical methods [25].

3. Results and Discussion

3.1. Compressive Strength Results from Diamond Core Tests

The compressive strength values (f'_c) obtained from the extracted concrete cores are presented in Figure 6. Six core samples were evaluated for each column. The maximum compressive strength was 26.42 MPa in column CI 02, whereas the minimum value was 22.62 MPa in sample P02 of column CE 01.

This represented a total range of dispersion of 3.80 MPa among all the evaluated samples. The resistance curves went down progressively through the sampling points (from P01 to P06), getting closer to an average value of approximately 25 MPa. In 100% of the evaluated cases, the obtained resistance surpassed the structural minimum design limit, which was established in 21 MPa.

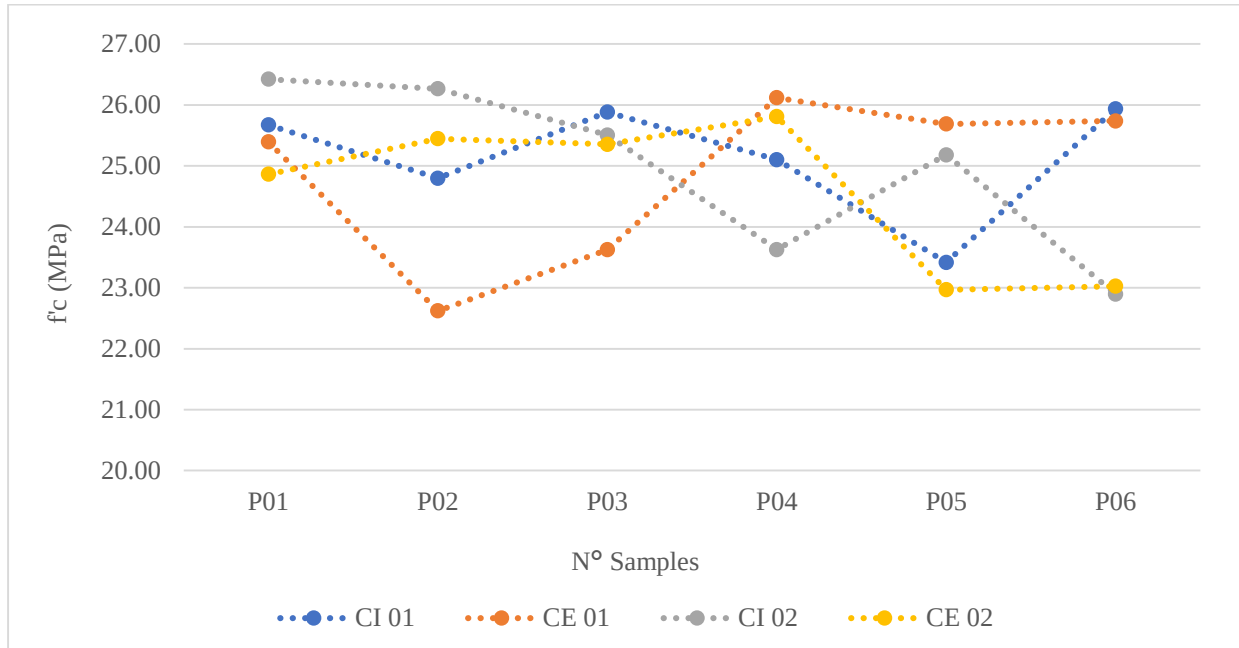


Fig. 6 Compressive strength from the diamond core test

Table 4. Compressive strength results from diamond core tests

Diamond Extraction Test - Strength (MPa)				
Description	CI 01	CE 01	CI 02	CE 02
P01	25.67	25.39	26.42	24.86
P02	24.80	22.62	26.27	25.45
P03	25.88	23.62	25.51	25.35
P04	25.10	26.12	23.63	25.81
P05	23.42	25.69	25.18	22.97
P06	25.94	25.74	22.90	23.02
MEAN	25.14	24.86	24.99	24.58
VARIANCE	0.91	1.98	2.04	1.59
MIN VALUE	23.42	22.62	22.90	22.97
MAX VALUE	25.94	26.12	26.42	25.81
STANDARD DEVIATION	0.95	1.41	1.43	1.26

According to Table 3, all the results obtained and depicted in this table were gotten from the compression tests of the concrete cores (diamond cores). This collected data exhibit a homogeneous mechanical resistance across the four evaluated fronts, with averages that fluctuate with small increments from 24.58 MPa to 25.14 MPa. The CI 01 sector stands out for representing the lowest-dispersion and controlled structural performance, it does not only registers the highest average resistance of 25.14 MPa, it also registers the minor dispersion of data represented in a Standard deviation (S) of barely .95 MPa and a variance (S^2) of 0.91MPa². This demonstrates a high uniformity in the pouring and curing process. In contrast, the fronts CE 01 and CI 02 represent the highest internal variation, reaching Standard deviations (S) of 1.41 MPa and 1.43 MPa respectively. This fluctuation is evidenced in the extreme values, where CI 02 register the individual highest peak in the entire samples with 26.42 MPa. In spite of the discrepancies, none of the individual values drop below the critical normative limits, like the 85% of the specific resistance according to the structural design normative like the ACI 318.

3.2. Ultrasonic Pulse Velocity Test

All the obtained results of the speed measures of the ultrasonic waves in 6 control points from P01 to P06 are exhibited in Table 4, and it is pictured in Figure 7. With regards the maximum speed, the maximum absolute velocity registered was of 3859 m/s, and it is localized in the point P06 of the column CI 01. In contrast, the minimum value is 3417 m/s, corresponds to the point P06 of the column CE 01. In all the recorded polls in the field, the average for the column CI 01 could be calculated, which reported a highest performance with a mean of 3727 m/s, followed by the CE 01 that has a performance of 3668 m/s, and the CI 02 with 3581 m/s. Finally, the column CE 02 with the lowest average of 3556 m/s. Regarding the behavior profiles by points, it was observed that the majority of the records remained stable over 3500 m/s. Only a fall below this threshold was registered in the point P06 of the series CE02, as shown in Figure 7, these obtained values corroborate the established classification in Table 1.

Table 5. Velocity and compressive strength results from the UPV test

Ultrasonic Pulse Velocity Test - Speed (m/s)				
Description	CI 01	CE 01	CI 02	CE 02
P01	3659	3677	3632	3536
P02	3695	3591	3589	3571
P03	3823	3652	3570	3681
P04	3753	3740	3559	3607
P05	3575	3666	3610	3527
P06	3859	3681	3527	3417
MEAN	3727.33	3668.83	3581.17	3556.60
VARIANCE	11213.47	2324.57	1405.37	7802.30
MIN VALUE	3575	3591	3527	3417
MAX VALUE	3859	3740	3632	3681
STANDARD DEVIATION	105.89	48.21	37.49	88.33

The outcomes obtained from the non-destructive tests of Ultrasonic Pulse Velocity (UPV) depicted in Table 4, indicate that the quality of the evaluated concrete is classified in all the control points as “good”, since it is placed within the standard range from 3500 to 4500 m/s. The CI 01 sector registers the high average velocity of 3727.33 m/s and shows the highest individual value of 3859 m/s, which denotes a highest density, less porosity and an excellent correlation with the obtained findings related to resistance from the diamond extraction. Based on the uniformity and homogeneity terms of the concrete mass, the sector CI 02 is the most consolidated one, exhibiting a very low dispersion with a Standard deviation (S)

of barely 37.49 m/s and a less variance (S^2) of the sampling with 1405.37 m²/s². In contrast. The CE 02 sector exhibits a light downward trend, registering a minor average of 3556.50 m/s and the minimum test point of 3417 m/s. This last reading is punctually placed in the category of “regular” quality with a range that goes from 3000 to 3500 m/s. This fluctuation in CE 02, added to the Standard deviation (S) is 88.33 m/s, suggests the localized presence of microcracks, it also suggest a higher internal porosity or a light segregation of the aggregate in the specific sector, without compromising the globalized structural integrity of the studies element.

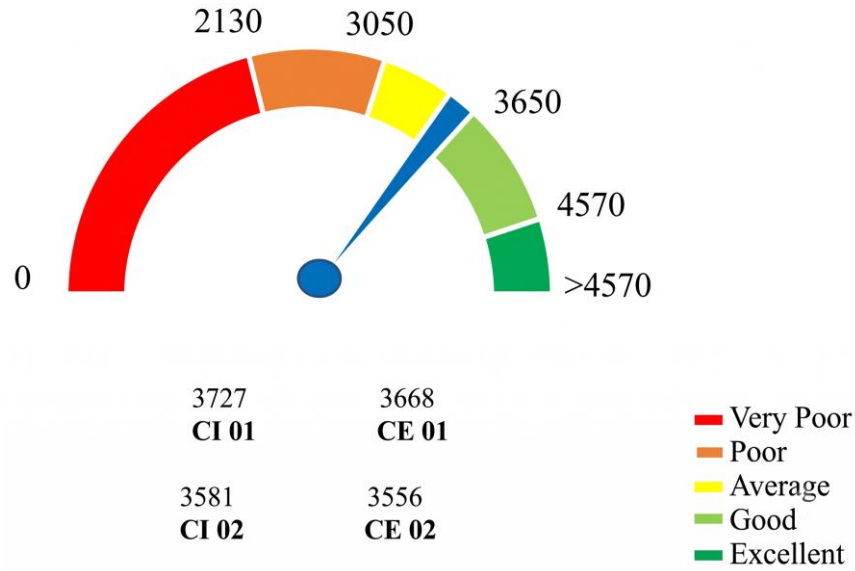


Fig. 7 Ultrasonic pulse velocity test results

Likewise, the ratio between the diamond core test and the ultrasonic pulse velocity was performed for all the test points. Nonetheless, data cleaning for homogeneity in order to avoid anomalies due to the transmission or interferences of some internal elements.

Thus, the ratio graph is found in Figure 8. On the other side, the forecast of the compressive strength based on the elasticity modulus was performed, with the empiric formula describes in Equation 2, as shown in Figure 9.

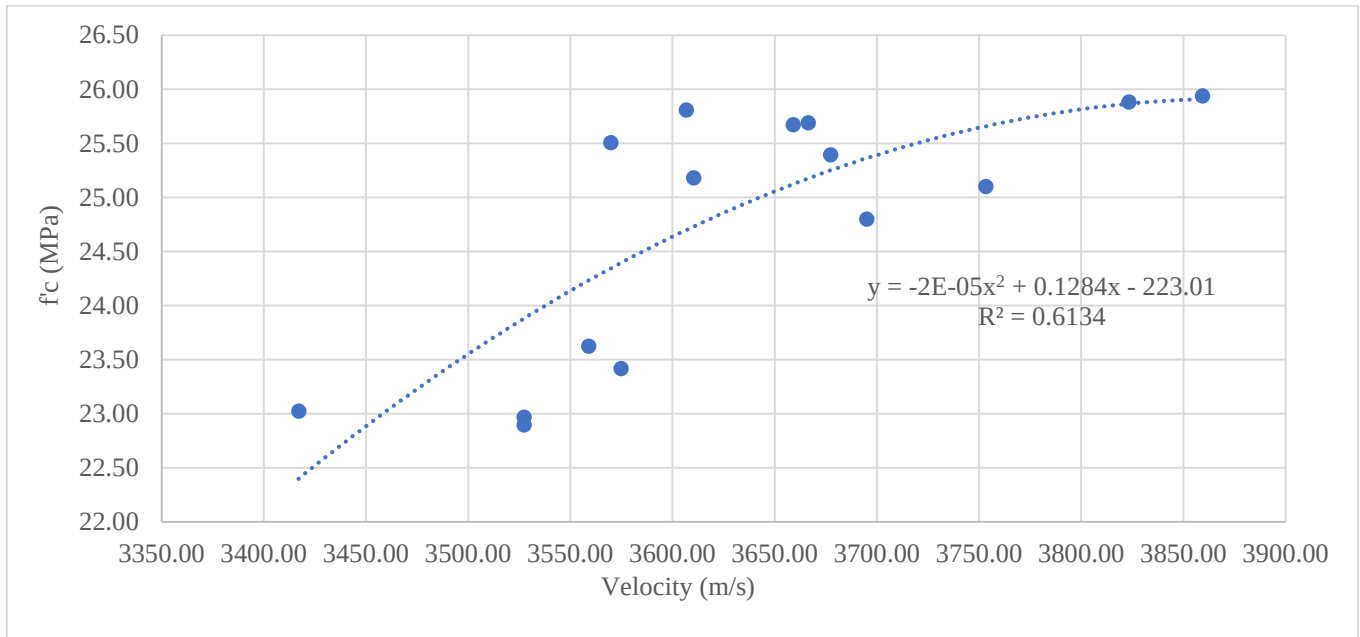


Fig. 8 Correlation between core strength and ultrasonic velocity

Figure 8 displays the correlation curve obtained after confronting the compressive strength of the extracted cores f'_c against the Ultrasonic Pulse Velocity (UPV). The math model that best adjusted to the dispersion of data was of the polynomial type in a second stage, defined by the showed equation in Figure 8. This model reached a coefficient of

determination R^2 of 0.6134. Visually, the model describes a pronounced positive slope in the range of low velocities from 3417 m/s to 3600 m/s, which tends to stabilize and create a small growth when approximating to higher speeds, situated between 3700 to 3859 m/s, where the resistances align and become constant, around 26.00 MPa.

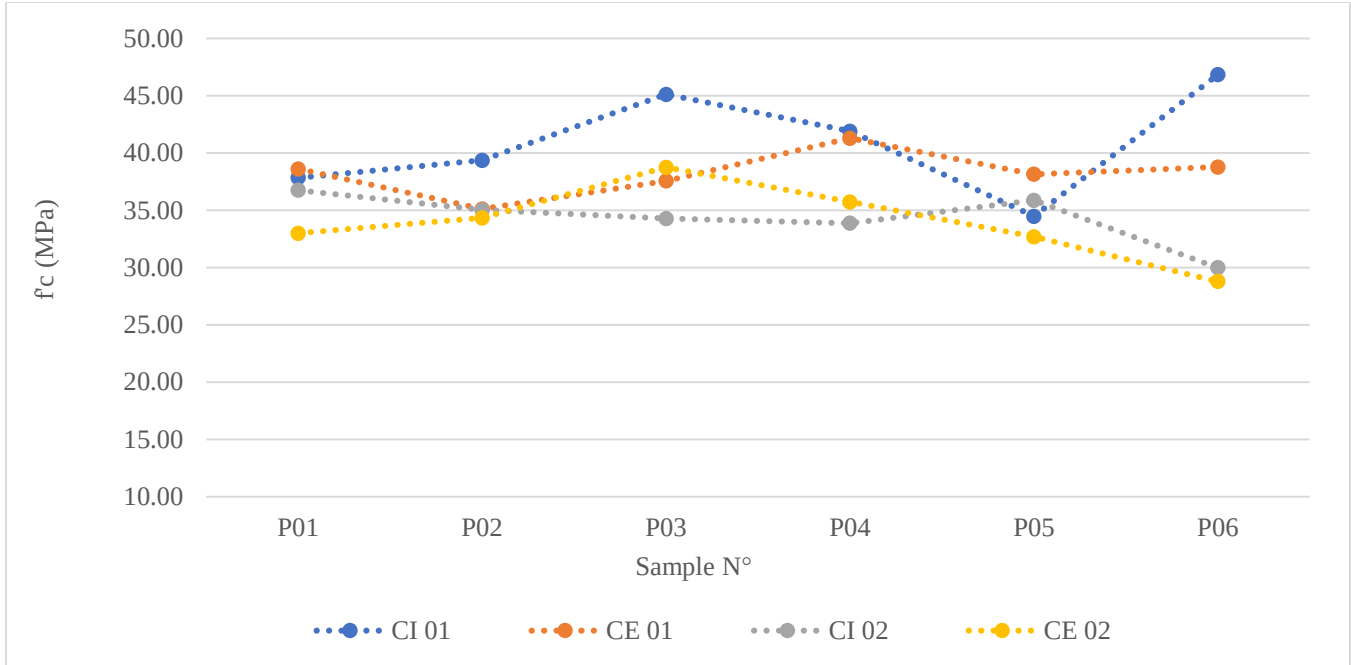


Fig. 9 Compressive strength via empirical formula

Figure 9 details the compression strength values that are projected according to the dynamic elasticity modulus for the 6 control points in each of the columns CI 01, CE 01, CI 02 and CE 02. The estimated strengths are distributed in a more ample range than the direct destructive tests, obtaining values that go from absolute value of 46.90 MPa in the column CI 01 in the P06 point and a minimum value of 28.70 MPa for the column CE 02 in the point P06. At the level of individual series, column CI 01 exhibited higher adequate values, depicting a progressive increment with remarkable peaks in column P03 with values that go from 45.20 MPa and P06. On the other hand, column CE 01 kept a more stable linear behavior, oscillating near the values of 39.00 MPa across the entire profile. In contrast, the columns CI 02 and CE 02 demonstrate a sustained decreasing trend in the final sections

and going to the point P06 towards their minimum estimated resistance.

3.3. Sclerometer

Table 5, shows each rebound index obtained from the average of the 15 grid points tested. This measurement was executed in the 6 points of each column, and an average value was obtained from each column. Likewise, the ratio between the diamond core test and the rebound index of the same filtered points in the ultrasound test (Figure 8), with the purpose to keep the sequence of the samples. Therefore, the ratio graph is found in Figure 10. On the other hand, the empirical forecast of the compressive strength was also performed, according to the Figure 3, based on the rebound index, these strengths are exhibited in Figure 11.

Table 6. Compressive strength results from the Sclerometry test

Rebound Hammer Test – Average Rebound Index				
Description	CI 01	CE 01	CI 02	CE 02
P01	31.50	32.40	32.40	36.00
P02	31.30	31.80	32.40	37.20
P03	31.20	32.90	31.90	36.50
P04	31.10	35.90	31.50	34.40
P05	30.60	34.70	31.10	32.00
P06	31.60	34.90	30.80	32.20
MEAN	31.22	33.77	31.68	34.72
VARIANCE	0.126	2.639	0.446	4.962
MIN VALUE.	30.60	31.80	30.80	32.00
MAX VALUE	31.60	35.90	32.40	37.20
STANDARD DEVIATION	0.354	1.624	0.668	2.227

The results were obtained after the sclerometer test that were calculated from 6 control points, as exhibited in Table 5. The interior columns registered a noticeably low dispersion: the CI 01 column concentrated their values in a narrow range that goes from a minimum value of 1.0 unit of a variation of 30.60 and a maximum variation of 31.60. This resulted in a Standard deviation (S) of 0.354 and a variance (S^2) of 0.126. In the same way, the column CI 02 reported a Standard deviation (S) of 0.688 with a variation (S^2) of 1.60 units.

On the contrary, the exterior elements displayed a significant higher variability. The CE 02 column reached an absolute maximum rebound value of 37.20 in the point P02 in this study, but it decreased down to a minimum of 32.00 in P05, consolidating the broadest dynamic range of 5.20 units, a high Standard deviation (S) of 2.157 and a high variance of the group (S^2) equal to 4.654. The CE 01 series depicted an intermediate homologous dispersion, with a Standard deviation (S) of 1.586 and a maximum value of 35.90 that was observed in the point P04.

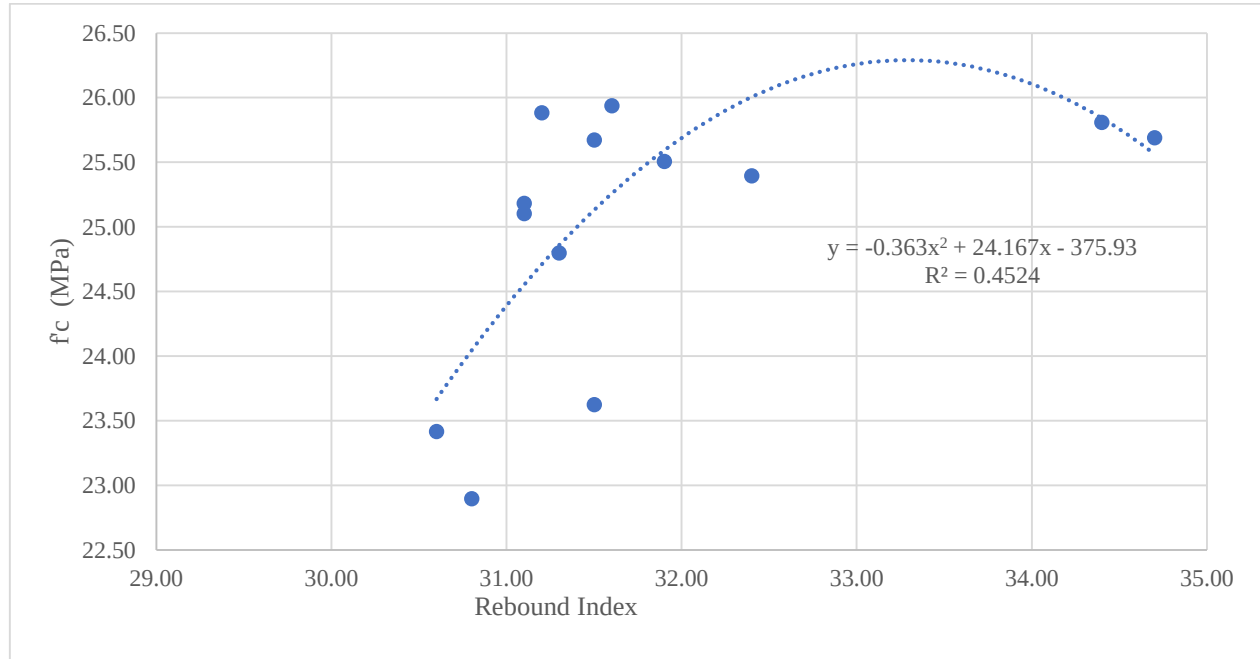


Fig. 10 Average rebound indices from the sclerometer

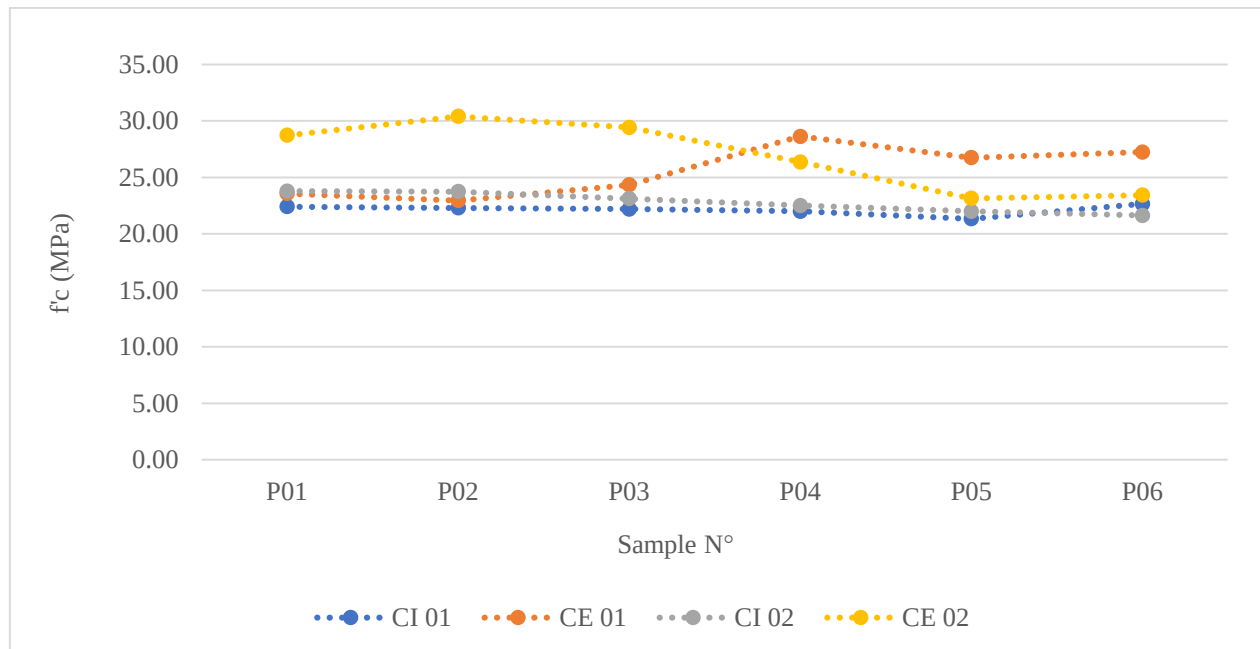


Fig. 11 Compressive strength via empirical graph

Figure 10 exposes the regression curve that was obtained after correlating the real compression strength of the f'_c against the superficial rebound index that was filtered through the sclerometer. The model identified an optimal behavior through the polynomial function, which reported a determination coefficient R^2 of 0.4524. The graphical distribution reveals that for the low and intermediate rebound values between 30.50 and 32.00 there is a high mechanical data dispersion in the vertical axis, concentrating resistance that go from 22.90 MPa to peaks of 26.00 MPa. Where most of the data related to the rebound index between 31-32 is found. Also, the polynomial curve reaches its maximum inflection point and draws a slight negative slope where final data is narrowly stabilized between 25.00 MPa and 26.00 MPa.

3.4. Multiple Correlation

As it could be observed in Figure 8 and Figure 9, the independent correlations were executed through the usage of each test equip. Nevertheless, if the ratios of both indicators (SonReb) are employed for the forecast of the compressive strength, a multiple correlation is obtained, and it is shown in

Figure 12: Thus, this SonReb correlation exhibited more compact features compared to a simple correlation because the SonReb correlation reached an increase in its determination Coefficient of Determination ($R^2 = 0.72$). Furthermore, the ANOVA test showed a p value of ($< 5\%$), demonstrating that a significant relation of the predictive variables exist (rebound index and ultrasound velocity).

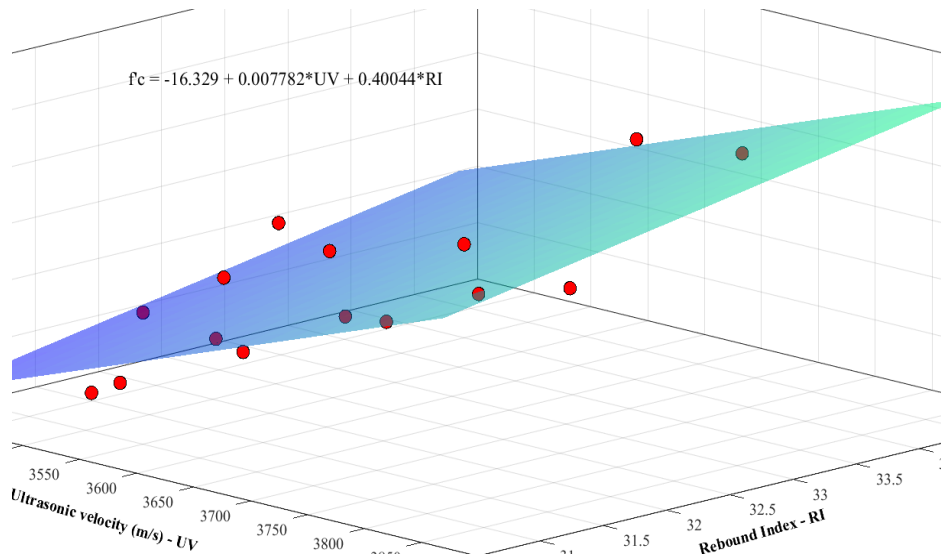


Fig. 12 Multiple regression based on the SonReb model

As can be observed in Table 7, suitable parameters were obtained through the statistical analysis.

Table 7. Statistical validation of the SonReb model

Indicator	Result
Number of observations	15
R^2	0.722
Adjusted R^2	0.675
F	15.55
Degrees of freedom	2, 12
Model p-value	0.00047
UPV coefficient	0.00778
UPV p-value	0.00027
RI coefficient	0.40034
RI p-value	0.0211
MAE	0.478 MPa
RMSE	0.601 MPa
MAPE	1.94%

Table 7 shows the statistical results obtained from the destructive and non-destructive tests for the SonReb model.

The model showed statistical significance, with a value of $p = 0.00047 < 0.05$. The interaction between ultrasonic pulse velocity and the rebound index contributed adequately to the model, obtaining low error values, with a MAPE of 1.94%. These results support the reliability of the calibrated model. These parameters were obtained under the same conditions for both types of tests.

3.5. Average Absolute Error

This current evaluation consolidates the set of data that is composed of 15 validated control points. The data base is a product of a thorough statistical cleaning process that was performed over a total simple of 24 recollected records in the field. This filtering process was methodologically critical for getting rid of atypical values that were caused by concrete personal differences or by external agent variations during the non-destructive tests. This optimization exhibits 15 optimal data that guarantees the extraction of valuable data for used

mathematical models and the technical reliability of the subsequent statistical analyses that are focused on the quantification of the relative error percentage ($\Delta\%$) of five estimation models against the real resistance that was obtained through the destructive test of Diamond Extraction (MPa).

After analyzing the predictive approaches based on the SonReb combined method (Sclerometer + Ultrasound), it is demonstrated that the correlation equation that are shown in Figure 12 represent the optimal mathematical model and the highest precision of this research. This optimal model registers the lowest global average of barely 1.94% and minimum individual deviations of up to 0.14% in the CI 01 sector. This outstanding technical performance is due to the fact that the integration of superficial hardness (Rebound Index - RI) and the internal compactness (measured by the Ultrasonic Pulse Velocity - UV) compensates the individual limitations of each trial. In a similar line of precision, the regional correlation equation found in Figure 10 validates its effectiveness with a controlled average error of 3.62%. In this sense, the abovementioned methodological alternative can be placed as

the second best scenario, since it's located below the critical threshold of 5%. On the contrary, when the SonReb method is applied in Figure 11's standardized empirical formulation, average error elevates up to 12.94%; this model shows a clear distortion in CI 01, with a peak error of 30.68%. Notwithstanding, it exhibits stabilization and adjustment rates notably lower than the 3% threshold in sectors CE01, CI 02 & CE 02.

Regarding the single-phase models that are exclusively dependent to Ultrasonic Pulse Velocity, a critical contrast between the local mathematical adjustment and the pre-established formulas is observed. Figure 8's calibrated correlation equation shows a high technical efficiency due to registering an average error of 2.95%, positioning it as a highly-reliable individual tool to estimate resistance towards compression in the cementitious matrix. In contrast, Figure 9 single-phased empirical prediction reports the most deficient and unacceptable predictive performance, with an overall average error of 48.90% and extreme deviations reaching 80.66% on sector CI 01.

Table 8. Percentage of variation of resistance to compression in the empirical models of correlation and estimation

Element	RI	UV (m/s)	Core Compressive Strength (MPa) Figure 6	SonReb	Sclerometer		Ultrasound	
				Correlation equation ($\Delta\%$) – Figure 12	Correlation equation ($\Delta\%$) – Figure 10	Empirical resistance prediction ($\Delta\%$) – Figure 11	Correlation equation ($\Delta\%$) - Figure 8	Empirical resistance prediction ($\Delta\%$) - Figure 9
CI 01	31.50	3659.00	25.67	3.55%	2.06%	22.70%	4.33%	47.47%
	31.30	3695.00	24.80	0.65%	0.29%	26.22%	0.04%	58.77%
	31.20	3823.33	25.88	0.14%	4.48%	20.55%	2.44%	74.38%
	31.10	3753.33	25.10	0.92%	2.13%	23.90%	0.14%	66.99%
	30.60	3574.67	23.42	1.39%	1.13%	30.68%	1.89%	47.28%
	31.60	3859.33	25.94	1.63%	2.57%	21.84%	2.53%	80.66%
CE 01	32.40	3677.33	25.39	0.52%	2.46%	7.16%	2.80%	52.10%
	34.70	3666.33	25.69	1.59%	0.42%	4.14%	4.20%	48.56%
CI 02	31.90	3569.67	25.51	5.03%	0.39%	9.34%	6.65%	34.46%
	31.50	3559.00	23.63	1.50%	6.43%	4.70%	0.32%	43.43%
	31.10	3610.33	25.18	3.81%	2.44%	12.61%	3.96%	42.51%
	30.80	3527.33	22.90	2.44%	5.07%	5.51%	2.03%	31.03%
CE 02	34.40	3606.67	25.81	1.14%	0.18%	2.14%	6.41%	38.48%
	32.00	3527.33	22.97	4.22%	11.91%	0.77%	1.72%	42.37%
	32.20	3417.00	23.02	0.57%	12.38%	1.80%	4.83%	25.06%
AVERAGE				1.94%	3.62%	12.94%	2.95%	48.90%

The mathematical models and resistance to compression estimations are obtained for each correlation case: Ultrasound (correlation equation described on Figure 8 and empirical estimation described in Figure 9); Sclerometer (correlation equation described on Figure 10 and empirical estimation

described in Figure 12); SonReb (equation described on Figure 12). Once the abovementioned is obtained, a comparative analysis of each model and estimation was performed in consideration to the real resistance values, compressive strength values obtained from the concrete cores

shown in Figure 6. In this sense, Table 6 shows the percentage of variation of said comparative analysis, as shown in Table 8.

4. Discussion

According to ACI (2021) [30], the extraction and compression of diamond core samples is the most direct method to determine the compression resistance of concrete structures. In this sense, for a specified concrete of $f'_c = 21$ MPa, the evaluation can be considered as structurally acceptable when the average of three diamond core samples is equal or superior to 85% of the specified resistance (17.85 MPa). In addition, no single core sample must show a value lesser than 75% of f'_c , equivalent to 15.75 MPa. The compressive strength results obtained from the extracted concrete cores ranged from a f'_c compression resistance that oscillates between a maximum value of 26.42 MPa of the CI 02 internal column, P01 sample, and showing a minimum of 22.62 MPa in the exterior column CE 01, sample P02. A finding of high critical relevance is that in 100% of the evaluated samples the 21 MPa limit for specified structural design was exceeded. According to Vivanco (2020) [31], "concrete core extraction is the most reliable and definitive in situ method to evaluate real resistance of hardened concrete, and it must be accepted, structurally speaking, if the average of the cores is at least 85% of the f'_c resistance design. In this study, the performance not only exceeded the abovementioned tolerance percentage, but it overtook by far the nominal design goal. The 3.80 MPa fluctuation observed between tests is usual in precast elements on site due to consolidation and internal segregation variables.

The non-destructive ultrasonic pulse trial concluded with a maximum absolute velocity of 3859 m/s in the P06 sample of CI 01 column, and a minimum of 3417 m/s in the P06 sample of the exterior CE 02. The overall averages determine that the column CI 01 has the best mechanical performance with a mean of 3727 m/s, descending gradually on the following elements until reaching a minimum mean of 3556 m/s in CE 02. With a clear exception of a single control point P06 in CE 02, all of the registered samples were stable over the critical threshold of 3500 m/s. According to Malhotra & Carino (2004) [32], "ultrasound pulse velocities located between a 3500 m/s and 4500 m/s categorize the measured concrete as 'Good', indicating that the cementitious matrix is compact, homogenous, and is free of significant internal discontinuities or gaps". This study's data firmly validate this condition, since the totality of the columns were located in said threshold. The targeted drop of 3417 m/s in the peripheral base (CE 02 - P06) can be attributed to local phenomena, such as premature evaporation or compaction difficulties due to environmental degradation caused by external exposure.

The sclerometric analysis showed statistically disperse results when comparing internal and external elements. The internal columns showed a notably high superficial homogeneity; for example, CI 01 sample concentrated its

rebound indexes between 30.60 and 31.60, resulting in an extremely low Standard deviation (S) of 0.354 and a variance of 0.126. On the contrary, the externally-exposed elements exhibited pronounced dispersion: the CE 02 column showed the absolute maximum rebound value of 37.20 in P02, yet it ostensibly dropped to 32.00 in P05, resulting in an elevated standard deviation of 2.157 and a variance of 4.656. Mehta & Monteiro (2014) [33] mention that "the sclerometer exclusively measures the hardness of concrete's superficial layer, approximately the first 25 to 30 millimeters, and it's highly susceptible to external factors such as accelerated carbonation, the type of formwork, and the environmental curing conditions, which usually inflate rebound values in dry areas or those exposed to external weather". This theoretical affirmation perfectly explains the reason why the external elements (CE 01 and CE 02) manifested a significantly higher variability in comparison to the internal columns, validating the hypothesis that sclerometry alone shouldn't be used to determine the resistance of a structural element, but it has to be used as a supplementary indicator of regularity.

By comparing the data of the destructive trials with non-destructive trials by means of statistical regression analysis, substantial discrepancies in each individual approximation (in comparison to their integrated use) were found. Firstly, simple correlation between the compression resistance of the f'_c extracted cores and the Ultrasonic Pulse Velocity (UPV) were adjusted to a second-degree polynomial model, reaching a determination R^2 coefficient of 0.6134, showing a clear increase of resistance in low velocity ranges between 3417 m/s to 3600 m/s, to then stabilize around 26.00 MPa in higher velocities. On the other hand, while evaluating in isolation the superficial hardness in comparison to real compression, the polynomial model decreased notably in precision, showing an R^2 coefficient of barely 0.4524 due to high vertical dispersion of mechanical resistances in the intermediate bounce rates between 30.50 and 32.00

Facing this situation, the fusion of both non-destructive indicators by means of the SonReb method showed a superior mathematical optimization, much more compact characteristics, and an increase of the determination coefficient to $R^2 = 0.72$. This relation consolidated by means of the polynomial tri-dimensional equation $f'_c = -16.329 + 0.007782 * UV + 0.40044 * RI$, which validated its high statistical significance by means of the ANOVA test, while reporting a p-value inferior to 5%, confirming that the combination between ultrasound velocity and the rebound index predicts the evaluated structural reality with much more certainty.

According to Bungey, Millard & Grantham (2006) [34], "the simple correlation coefficients based on a single non-destructive trial tend to lack sufficient precision due to the fact that ultrasound pulse is sensitive to internal gaps, while the sclerometer is sensitive to surface conditions; in contrast, the

combination of both by means of the SonReb method mitigates the intrinsic disadvantages of each individual technique, ostensibly increasing the reliability of the in situ estimation model." The experimental results obtained in the present investigation conclusively validate this theoretical principle, since the transition a deficient R^2 of 0.4524 (isolated sclerometer) to an R^2 of 0.72 (combined SonReb) shows that the integration of the internal dynamic properties of concrete with its surface mechanical characteristics neutralizes the local anomalies, offering a highly-reliable prediction tool to control structural quality without massively recurring to destructive methods.

The data gathered from the tests show that the calibrated SonReb model offers a better adjustment and a lower prediction error within the current database, with $R^2 = 0,722$, R^2 adjusted = 0,675, MAE = 0,478 MPa, RMSE = 0,601 MPa and MAPE = 1,94 %. These indicators correlate with other coetaneous approaches that assess combined non-destructive methods by means of statistical metrics such as R^2 , MAE, RMSE and MAPE [18], as well as studies that report a more precise estimation of the concrete's strength when ultrasound pulse velocity and rebound index are used jointly, instead of doing so independently [17]. A recent multivariable NDT model, locally calibrated, which combines measurements with a rebound hammer and ultrasound pulse velocity, reported a value of $R^2 = 0,79$, RMSE = 1,46 MPa and MAE = 1,26 MPa [19]. Although its determination coefficient was higher than the one obtained in the present study, the direct numerical comparison must be interpreted cautiously, since the concrete mixtures, the strength ranges, the size of the samples, the predicting variables and the experimental conditions were different.

Within the present database, the combination of Ultrasound Pulse Velocity (UPV) and the rebound index reduced the average prediction error to 1,94 %, in comparison to the value of 2,95 % from the UPV calibrated model and the value of 3,62 % from the rebound calibrated model. This improvement may be attributed to the complementary information provided by the two non-destructive trials: The UPV measures wave propagation and the concrete's internal continuity, whereas the rebound index is mainly related to surface hardness. Therefore, its combined use reduces part of the observed uncertainty when any of the measurements are observed independently.

Regarding ASTM C805/C805M, this standard indicates that the rebound index requires a relationship with strength, but it also shows that it should be used in a complementary way to obtain better results [20]. UPV evaluates the uniformity and relative quality of concrete, as well as its initial or surface condition [21]. In addition, ACI 228.1R-19 recommends establishing specific relationships through regression and statistical analysis [35]. This means that the SonReb model, when correctly applied with suitable core samples, can provide good results.

In Peru, self-construction is a widespread practice and many of the existing structures were built this way. This evidences a high rate of uncertainty when characterizing the concrete, resulting from a lack of quality control during the construction phase. In this sense, notwithstanding the fact that the ultrasound tests indicates that the quality of the concrete is either regular or good, it doesn't ensure its integrity. This is because several factors influence the measurements, such as the mixture proportions, the presence of reinforcing steel beams, the quality of the aggregates, etc [36, 37]. Besides, in spite of measuring several structural elements with the same mixture concentrations [38], it doesn't ensure a higher Determination Coefficient ($R^2 = 0.61$) as shown in Figure 8. This is because each element may exhibit different wave velocities, affected by the abovementioned factors. Nonetheless, the correlation with core compressive strength is often close to 2.95% on average. Regardless, when the empirical formulation is applied, the resulting overestimation would be quite excessive (see Table 6).

The sclerometry test is another test that would help to characterize the analyzed material. Regardless, by itself it cannot efficiently capture the structural element's real resistance; as seen in Table 6, the values suffer an average variation of 12.94% in relation to real resistance. Although, when calibrated against core compressive strength, the resulting variation is 3.62%, supposing a considerable approximation. Yet, This limitation should be considered when the Determination Coefficient is low ($R^2 = 0.45$), meaning that there are other factors that influence uncertainty, such as the hardness of the superficial layer, carbonation, internal porosity, and such [39]. Therefore, this impliceance must be taken into account when considering the correlation between several structural elements, despite sharing the same building process.

These results evidence a clear overestimation of the real resistance and they show that the direct use of manufacturer's data sheets or specifications for the equipment without prior calibration against core compressive strength lack technical validity. In this sense, the results validate that the depuration of data and the usage of combined calibrated models (Figure 12) and/or single-phased models (Figure 8) are the only viable options to represent suitable alternatives for improving the reliability of concrete strength assessment in the evaluated elements of the evaluated concrete diagnosis.

Several factors influence the characterization of the material, limiting the possibility of choosing a clear, reliable approximation to estimate compression resistance. Regardless, the practical way to reduce this uncertainty rate is the application of the SonReb method, combining the Rebound Index variable and the Ultrasound Pulse Velocity by means of a multiple regression, in order to measure multiple, similarly-built structural elements (in this case, concrete columns; CI 01, CE 01, CI 02, CE 02). By utilizing the

aforementioned method, a low average variation was obtained (around 1.94%). Additionally, reliability depends substantially on the Rebound Index and the Ultrasound Pulse Velocity, ensuring an increase in the Determination Coefficient ($R^2 = 0.72$), obtaining a considerably lower value than the significance level ($0.00047 < 0.05$). To conclude, it's important to mention that all of the incidental factors cannot be covered holistically for concrete characterization, therefore, the NTP 339.034 normative indicates the relevance of calibration against core compressive strength.

4.1. Study Limitations

The main limitation was the availability of suitable laboratories to carry out the sampling and to maintain appropriate environmental conditions for each test. In the tests performed, climatic differences were present, and the evaluated structures did not have a known construction date or previous strength record. For this reason, these parameters were assumed based on estimated controls from Peruvian standards, considering the quality of aggregates for a concrete mixture of $f'c = 210 \text{ kg/cm}^2$. However, the materials used can modify this strength and other necessary parameters.

The scope of this study was limited to the characterization and estimation of the concrete's compressive strength in the assessed columns by means of destructive and non-destructive trials. The study did not include a global structural assessment of the building, such as the load capacity, the concrete frame's verification, the seismic demand, the structural stability or the structural element-level safety analysis. Therefore, the results must be interpreted as an assessment of the concrete's strength and of the material's state within the assessed elements, instead of a complete assessment of the building's structural safety.

For the evaluation, data collection, and sampling process, the research focused on structural concrete elements and did not include human participants. Only extraction and measurement equipment were used. These activities were carried out under proper safety conditions and with the support of technical personnel in charge of the handling process. The extraction of samples was performed with the authorization of the owner and the support of the laboratory. All non-destructive tests, sample extraction, and laboratory compression tests were carried out according to the applicable technical procedures and safety requirements.

5. Conclusion

The results show that the compressive strength measured in the tested concrete exceeded the reference design strength of 21 MPa in all evaluated samples (which is an essential requirement). Non-destructive tests complemented this strength assessment: the ultrasound pulse velocities were stable and predominantly superior to the 3500 m/s threshold, indicating generally uniform concrete quality and no evidence of major internal discontinuities within the limitations of the

UPV measurements in the material's composition. Notwithstanding, the observed discrepancies in the sclerometer's rebound index as well as the slight reduction in element CE 02's velocity imply that environmental external factors alter the concrete's surface properties. This emphasizes on the necessity to implement rigorous curing processes when building in exteriors and demonstrates that the sclerometer must not be employed alone due to its susceptibility to environmental conditions, but it must be combined with ultrasound to guarantee a reliable and precise characterization of the element's internal resistance. The SonReb method is verified as the best mathematical decision, since only-sclerometer measurements had very little precision ($R^2 = 0.45$). Regardless, measurements resulting from utilizing the SonReb method turned out to be far more precise ($R^2 = 0.72$), proving that the aforementioned non-destructive method is much more precise and reliable.

Characterizing the concrete's resistance is still one of the most complicated challenges in forensic engineering, even more so if the measured structures were built without following a technical guide or without the participation of a professional builder. This is the reason why the mathematical models used in this article were based on non-destructive trials while taking into account the related implications.

The mathematical model utilized for ultrasound and sclerometer testing, independently calibrated against the compressive strength obtained from concrete cores, estimates compression resistance with an average variation of $\pm 2.95 \%$ and $\pm 3.62 \%$ respectively between the same structural types. Regardless, when opting for these application methodologies one must take external and internal factors into account.

The practical approximation to reduce the abovementioned intervening factors is the application of the SonReb mathematical model, which estimates the compression resistance with an average variation of $\pm 1.94 \%$ between similar structure types, a confidence level lower than 5% and a higher dependency of these two trials.

For future projects, and to conclude the present article, it's actively recommended to not rely on isolated sclerometer results, specifically results on structural elements exposed to environmental external factors (such as wind, rain, prolonged sunlight, etc.), since the climatical conditions alter the superficial hardness of concrete, distorting the data. Instead, the SonReb (Ultrasound + Sclerometry) method must be implemented, allowing to monitor the concrete's quality in a fast, cheap, and non-invasive way. This method limits concrete core extraction to final validation at locations requiring further verification in highly-dubious points.

To conclude, high caution must be present in the curing process of the exterior columns in order to avoid resistance loss in their base or peripheral surfaces.

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