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Evaluation of the compressive strength of a reinforced concrete structure using different SonReb estimation methods

Evaluación de la resistencia a compresión de una estructura de hormigón armado utilizando diferentes métodos de estimación de SonReb

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Abstract

This document discusses the results obtained in the estimation of compression strength through the readings of the rebound hammer and ultrasonic pulse velocity on 9 columns of reinforced concrete. The estimation was performed by applying different SonReb models. The objective of the study is to evaluate which of the applied models is more consistent with the compression resistance value of 27.0 MPa obtained by press-breaking assay, for concretes manufactured with Ordinary Portland Cements P-35 (Type I) of domestic production and aggregates from Cuban quarries. The results obtained showed that the models proposed by RILEM and Tanigawa et al. were closest to the reference value with percentage difference below 4%. This research will allow the performance of non-destructive tests with more accurate results, in the restoration processes of the Historic Center of Havana, Cuba.

Keywords: Rebound Hammer; Ultrasonic Pulse Velocity; SonReb; Concrete; Compressive strength.

Resumen

En el presente trabajo se analizan los resultados obtenidos en la estimación de la resistencia a la compresión a través de las lecturas del índice esclerométrico y la velocidad del pulso ultrasónico en 9 columnas de hormigón armado. La estimación se realizó aplicando diferentes modelos SonReb. El objetivo del estudio es evaluar cuál de los modelos aplicados es más consistente con el valor de resistencia a la compresión de 27.0 MPa obtenido por ensayo de rotura en prensa, para hormigones fabricados con Cementos Portland Ordinarios P-35 (Tipo I) de producción nacional, y áridos de las canteras cubanas. Los resultados obtenidos demuestran que los modelos propuestos por RILEM y Tanigawa et al. expresan resultados más próximos al valor de referencia, con un error inferior al 4%. Esta investigación permitirá la realización de ensayos no destructivos con resultados más certeros, en los procesos de restauración del Centro Histórico de La Habana, Cuba.

Palabras clave: Esclerometría; Velocidad de pulso ultrasónico; SonReb; Hormigón; Resistencia a Compresión

1. Introduction

One of the social requirements that has been acquiring more concern over the past decades is the need to live in a safe and durable property (Hong et al., 2020). Various techniques such as resistance to penetration, pull-out and pull-off, extraction of concrete cores, resonance and permeability, allow evaluating the structural strength of a concrete building, however, they have as drawbacks the research time, high costs and the physical aggression to the structure. This problem has led to the need to develop non-destructive testing methods (NDT) that allow economically, quickly and effectively to estimate the compressive strength, state of conservation and durability of a building.

NDTs are those techniques that are performed during the course of an inspection, test or evaluation to obtain information about the state of conservation of a material. The purpose is to determine the quality and integrity of the parts and components of a structure without affecting their performance, or functions for which they were designed (Helal et al., 2015); (Hussein and Abdi, 2021).

Among the most important factors that support the use of NDTs are the possibility of evaluating the vulnerabilities of the building from the detection of damaged areas, estimation of compressive strength (fc) and variations in quality according to the project requirements (Breysse et al., 2017); (Chandak and Kumavat, 2020).

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The quality of concrete is generally expressed in terms of resistance, because buildings must be designed to withstand different types of loads. Concrete is a material that is made up of cement, coarse and fine aggregates, water and additives, and once it sets it is necessary to know the acquired compressive strength value, mainly at 28 days. For this purpose, numerous calculation equations have been developed that allow estimating the concrete's fc from the values of the Rebound Hammer (RN) (Lima and Silva, 2000), the ultrasonic pulse velocity (UPV) (Hannachi and Guetteche, 2012); (Popovics, 1991) or the measurement of the resistivity (ρ) of the concrete (Araújo and Meira, 2021).

Another widely applied methodology is the SonReb method, which combines the results of the RN and the UPV. Since its implementation in the 60s of the last centuries by Facaoaru (Facaoaru, 1969), this has become the most used NDT to estimate the fc of concrete.

Since it is a non-destructive technique, the accurate and precision of the results may be affected by errors in the preparation and setting of the concrete, age of the structure, presence of reinforcements, mix design, carbonation, porosity, cracks, characteristics of the aggregates and environmental parameters such as temperature and relative humidity (Cristofaro et al., 2020); (Hussain and Akhtar, 2017).

Cuban standards do not have implemented the SonReb method as a valid NDT procedure for estimating the fc. In this sense, they only propose the use of RN (NC 246, 2003), and the UPV (NC 231, 2002) as separated methodologies to estimate the concrete's compressive strength and quality. In the bibliographic research carried out, only two previous investigations in Cuba based on the SonReb method were identified (Navarro et al., 2019); (Ricardo, 2018).

The objective of this study is to identify which SonReb model is more feasible to be used in real structures, for the current construction materials available in Cuba. For this, eight models were correlated to identify in which one of them a closer value to the concrete reference developed, is obtained. The study was carried in a historic building under restoration phase in the Historic Center of Havana. The rehabilitation required the construction of columns and beams, of which nine columns were chosen to carry out the study. The concrete used was designed from aggregates extracted from Cuban quarries. The reference specimens were taken in-situ, from the same concrete mix with which the reinforced concrete columns were formed.

2. Materials and Methods

2.1. Mix Design

For the production of the concretes, ordinary Portland cement (OPC) P-35 (Type I) was used, from the Cementos Curasao Factory, located in the Mariel municipality, Artemisa province. (Table 1) shows its main characteristics, in accordance with the requirements of the Cuban Standard (NC 1340, 2021).

***Table 1**. Physical properties of OPC (P-35)*

Properties	Values	Acceptance
Specific surface (Blaine) (cm^2/g)	3317	min. 2800
Fineness (%)	1,7	max. 10
Initial setting time (min)	102:00:00	min. 45
Final setting time (h)	3:02:00	max. 10
Volumetric weight (kg/m^3)	1168	-
Density (g/cm^3)	3,15	-
Normal consistency (%)	24,5	-

The fine and coarse aggregates used in the preparation of the concrete mix are of natural origin, extracted from the Dragon Camoa quarry located in the Mayabeque province, and from the Alacranes quarry located in the Matanzas province. All the tests were carried out according to the corresponding Cuban Standards (NC 177, 2002); (NC 181, 2002); (NC 182, 2002); (NC 186, 2002). (Table 2) and (Table 3) details the physical properties of the aggregates and their granulometric distribution.

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***Table 2**. Physical properties of fine and coarse aggregates*

Properties	Sand	Coarse
Current specific gravity (g/m³)	2.65	2.62
Saturated specific gravity (g/m³)	2.70	2.66
Apparent specific weight (g/m³)	2.75	2.70
Percentage absorption (%)	0.60	1.50
Loose volumetric mass (kg/m³)	1443	1309
Compacted volumetric mass (kg/m³)	1616	1462
Percent of gaps (%)	39.6	44.8
Finest Material-Sieve 200 (%)	3.00	1.20

***Table 3.** Granulometric distribution of the aggregates used*

Aggregates	Sieves (mm)								
	19.1	12.7	9.52	4.76	2.38	1.19	0.59	0.295	0.149
Fine	100	100	95	90	74	45	28	14	5
Coarse	100	98	63	6	2.5	0.0	0.0	0.0	0.0

A ratio of fine and coarse aggregate of 55/45 respectively was used. The water/cement ratio used was 0.45. The estimated compressive strength (fc) is 30.0 MPa. To improve the workability of the fresh concrete, the additive MAPEI Dynamon SRC-20 was used. This is an acrylic-based super-fluidizing additive (advanced second generation) modified for pre-mixed concretes characterized by a low water/cement ratio, high mechanical resistance and long maintenance of workability. The settlement measured by the Abrams cone was between 14 and 16 cm. The amount of materials to be used for a cubic meter of concrete is shown in (Table 4).

***Table 4.** Dosage and quantity of materials*

Materials	1 m³ of concrete
Relation a/c	0.45
Cement P-35 (kg)	490.0
Water (L)	220.0
Fine Aggregates (kg)	815.0
Coarse Aggregates (kg)	750.0
Additive (L)	35.0

3. Experimental Methodology

The fresh concrete samples for the preparation of the test cores was carried out directly in the construction site in accordance with the Cuban Standard (NC 167, 2002). In this study all assays of the concrete cores were executed by the National Laboratory of Applied Research (ENIA). The test cores were kept under curing in the pool for 28 days and subsequently tested by breaking in a concrete press. The average fc result emitted by the laboratory was 27.0 MPa. This will be the reference value for comparison with the results obtained by the different SonReb methods used.

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For the application of the experimental methodology, nine columns were selected (C2, C4, C5, D2, D4, D5, E2, E4, E5), which were under construction on the second level of the building. They have a cross section of 300 x 300 mm, and a length of 4500 mm. In each column, two test points were prepared: from the base the first located at 1680 mm and the second at 2680 mm, with the purpose of evaluating the columns in the lower and upper part. This makes it possible to identify possible significant differences between the mass of the concrete as a result of execution errors. In each test area, 10 measurements were made, for a total of 20 results for each column. All measurements were made between 28 to 56 days of age.

For the selection of the SonReb methods, a bibliographic research of the empirical equations developed was carried out. A total of eight equations were selected, ranging from its beginnings in 1979 to the present in 2020. (Table 5) shows the equations used.

***Table 5**. SonReb equations applied for estimation of compressive strength*

Year	Author	Equation	Units (fc, UPV)	Correlation type
1979	Bellander (Bellander, 1979)	$fc = -25.568 + 0.000635\mathrm{RN}^3 + 8.397\mathrm{UPV}$	MPa, km/s	Polynomial
1979	Meynink et *al*. (Meynink & Samarin, 1979)	$fc = -24.668 + 1.427\mathrm{RN} + 0.0294\mathrm{UPV}^4$	MPa, km/s	Polynomial
1993	RILEM (RILEM NDT 4, 1993)	$fc = 9.27 \times 10 - 11.11RN^{1.4} \times UPV^{2.6}$	MPa, m/s	Power
1994	Tanigawa et *al*. (Faella et al., 2011)	$fc = 0.9RN + 0.022\ UPV - 0.94$	MPa, m/s	Linear
1996	Arioglu & Köylüoglu (Arioglu & Köylüoglu, 1996)	$fc = 0.00153 \times (RN^3 \times UPV^4)^{0.611}$	MPa, km/s	Power
1996	Ramyar et *al*. (Ramyar & Kol, 1996)	$fc = -39.570 + 1.532RN + 5.0.614UPV$	MPa, km/s	Linear
1999	Khedar et *al*. (Khedar, 1999)	$fc = 0.0158RN^{1.1171} \times UPV^{0.4254}$	MPa, m/s	Power
2020	Chandak & Kumavat (Chandak & Kumavat, 2020)	$fc = 0.0841RN^{-0.572} \times UPV^{0.945}$	MPa, m/s	Power

3.1. Equipment used

As non-destructive techniques for estimation by SonReb, a Proceq digital Schmidt Hammer was used. The surface was prepared according to current regulations (ASTM C805, 1997); (NC 246, 2003). The program used to download the data was Proceq Hammerlink®. A Proceq Pundit Lab+ ultrasound with 54 KHz transducers was used. The data was downloaded by the software Proceq PunditLink®. The measurement technique used was "Direct Transmission". To locate the reinforcing bars embedded in the columns, a rebar locator Proceq Profoscope was used (Figure 1) and (Figure 2).

***Figure 1.** Undergoing of measurements on a column*

***Figure 2**. Area of column selected for measurement with rebar location marked with crayon*

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3.2 Statistical analysis

Due to the fact that the experiments were carried out on a real structure undergoing restoration, the execution times of tests are limited. Because of this, it is important to ensure that the greatest amount of results obtained are valid and consistent. These were analyzed using descriptive statistics. For the statistical analysis of linear regression, normal distribution, standard deviation (SD), coefficient of variation (CV) and construction of graphs, the program OriginPro 2018 SR1 was used. Microsoft Excel 2019 program was used to organize the data.

4. Results and Discussion

(Table 6) and (Table 7) show the results obtained from the UPV and RN measurements performed on the columns. The statistical analysis reflects that, in all the elements studied, the CV did not exceed 10% with a normal distribution of the data. The total data analyzed (n) for the application of the models was 162 results. For mathematical development, UPV was established as an independent variable, while RN was the dependent one.

Table 6. *Results of measurements and statistical parameters*

	Columns							
	C2		C4		C5		D2	
	UPV (m/s)	RN Q value	UPV (m/s)	RN Q value	UPV (m/s)	RN Q value	UPV (m/s)	RN Q value
	3597.1	42	4032.3	40.5	3512.9	42.5	3754.7	42.5
	3597.1	40	4087.2	33.5	3512.9	38	3731.3	37.5
	3575.7	41	4059.5	43.5	3533.6	41.5	3778.3	44.5
	3597.1	40.5	4087.2	38.5	3492.4	42.5	3754.7	39.5
	3575.7	41	4115.2	38	3533.6	42.5	3778.3	40.5
	3597.1	40	4115.2	37.5	3492.4	40	3754.7	37.5
	3597.1	40	4087.2	40	3492.4	48	3778.3	41.5
	3597.1	37.5	4115.2	36	3492.4	44.5	3778.3	35.5
	3618.8	41.5	4115.2	41.5	3492.4	47.5	3802.3	42
	3952.6	42	4115.2	40	3492.4	41.5	3802.3	41
	3952.6	41.5	3708.3	44	3802.3	43	3851.1	45.5
	3952.6	41	3708.3	40.5	3802.3	41	3876	41.5
	3952.6	41.5	3708.3	42.5	3826.5	44.5	3901.2	44
	3952.6	39	3731.3	39.5	3802.3	45	3851.1	45.5
	3952.6	39	3731.3	40	3826.5	46.5	3876	42
	3952.6	41.5	3731.3	41.5	3802.3	42	3851.1	44.5
	3952.6	40	3708.3	40.5	3826.5	45.5	3876	39.5
	3952.6	40	3731.3	45	3826.5	47.5	3876	45
Mean	3773.6	40.5	3927.1	40.1	3642.3	43.5	3815.1	41.6
SD	184.32	1.19	192.09	2.82	159.05	2.78	54.15	2.94
CV (%)	4.88	2.93	4.89	7.03	4.37	6.40	1.42	7.06

Table 7. *Results of measurements and statistical parameters*

	Columns									
	D4		D5		E2		E4		E5	
	UPV (m/s)	RN Q value	UPV (m/s)	RN Q value	UPV (m/s)	RN Q value	UPV (m/s)	RN Q value	UPV (m/s)	RN Q value
	3512.9	38.5	3640.8	42	3640.8	43.5	3826.5	43	3618.8	42
	3452.2	41	3663	40.5	3640.8	41.5	3826.5	41.5	3640.8	38.5
	3472.2	37	3663	41.5	3663	42	3826.5	43.5	3640.8	38.5
	3575.7	37.5	3708.3	45.5	3640.8	48.5	3802.3	42	3640.8	43
	3554.5	35.5	3708.3	41.5	3640.8	43	3826.5	47.5	3663	42.5
	3452.2	37	3754.7	43.5	3663	42	3826.5	40.5	3685.5	43
	3492.4	40.5	3685.5	42	3663	43.5	3802.3	38.5	3663	40
	3472.2	38.5	3731.3	44.5	3663	38.5	3826.5	38	3663	39
	3512.9	37	3708.3	42.5	3663	43	3826.5	45.5	3663	39.5
	3472.2	37.5	3731.3	40.5	3663	43.5	3851.1	44	3685.5	38
	3533.6	43.5	3685.5	44.5	3778.3	42.5	3731.3	40.5	3731.3	43.5
	3533.6	41	3685.5	46.5	3778.3	39.5	3731.3	36.5	3754.7	45
	3533.6	43	3685.5	42	3708.3	42	3731.3	39	3754.7	45.5
	3554.5	43	3685.5	45.5	3754.7	41	3731.3	41.5	3754.7	42.5
	3533.6	42	3685.5	43	3778.3	36.5	3731.3	45	3778.3	39.5
	3554.5	42	3708.3	45	3640.8	42	3731.3	47	3754.7	43
	3554.5	45	3685.5	44.5	3754.7	38.5	3754.7	43	3778.3	38.5
	3554.5	45.5	3685.5	45.5	3731.3	43.5	3731.3	46	3754.7	43.5
Mean	3517.8	40.2	3694.5	43.3	3692.5	41.9	3784.1	42.3	3701.4	41.3
SD	39.57	3.05	27.24	1.88	54.32	2.61	47.35	3.17	54.86	2.43
CV (%)	1.12	7.58	0.74	4.33	1.47	6.22	1.25	7.48	1.48	5.88

The average UPV obtained in all cases is higher than 3500 m/s, which responds to high-quality concrete (NC 231, 2002). Similarly, the RN recorded show the Q value> 40 for an estimated compressive strength greater than 30 MPa (NC 246, 2003). The average results are shown in (Table 8).

Table 8. *Average results of UPV and RN measurements*

Column No.	ID	UPV average (m/s)	RN average
1	C2	3773.68	40.50
2	C4	3927.10	40.14
3	C5	3642.37	43.53
4	D2	3815.09	41.64
5	D4	3517.88	40.28
6	D5	3694.52	43.36
7	E2	3692.55	41.92
8	E4	3784.17	42.36
9	E5	3701.42	41.39

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For the calculation of the fc from the proposed models (Table 9), a greater dispersion is observed in the CV of the results, which respond to the design of each equation. Based on the results obtained, the models with the best approximation to the reference value are RILEM and Tanigawa et al. with 26.29 MPa and 26.07 MPa respectively (Figure 3), with an error for both cases of less than 4% (Figure 4). In (Figure 5) it is observed how some models have a linear behavior, while others shown a greater dispersion of the data. Since these models are based on linear, polynomial and power equations with an influence of the RN and UPV values in its equations to calculate the fc, it is important to determine which of these variables of the equation is more or less influential.

Table 9. *Results of the statistical analysis of the values obtained*

Author	ID	n total	fc Mean	Standard Deviation	Coefficient of Variation (%)
RILEM	fc1	162	26.29	3.12	11.88
Bellander	fc2		53.30	9.12	17.11
Meynink et *al*.	fc3		41.00	3.82	9.33
Tanigawa et *al*.	fc4		26.07	3.50	13.60
Raymar et *al*.	fc5		43.62	4.12	9.46
Arioglu & Köylüoglu	fc6		36.40	4.89	13.45
Kheder	fc7		17.99	1.29	7.18
Chandak & Kumavat	fc8		23.67	1.40	5.91

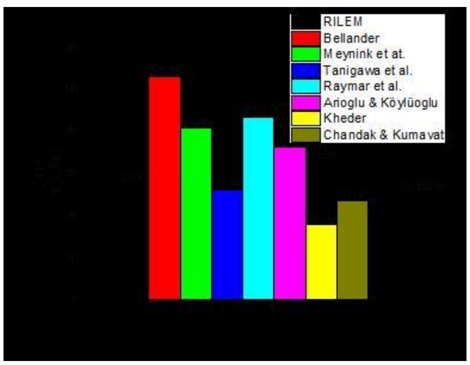

Figure 3. *Results of fc obtained with respect to the reference value of 27.0 MPa*

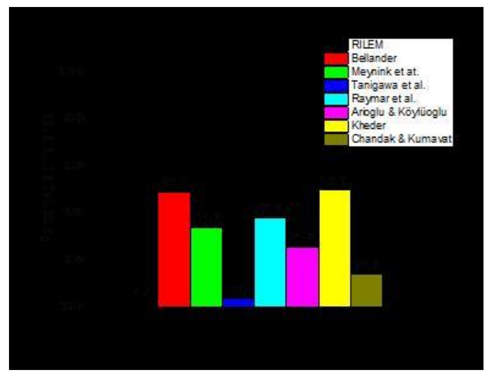

Figure 4. *Percentage of difference with respect to the reference value*

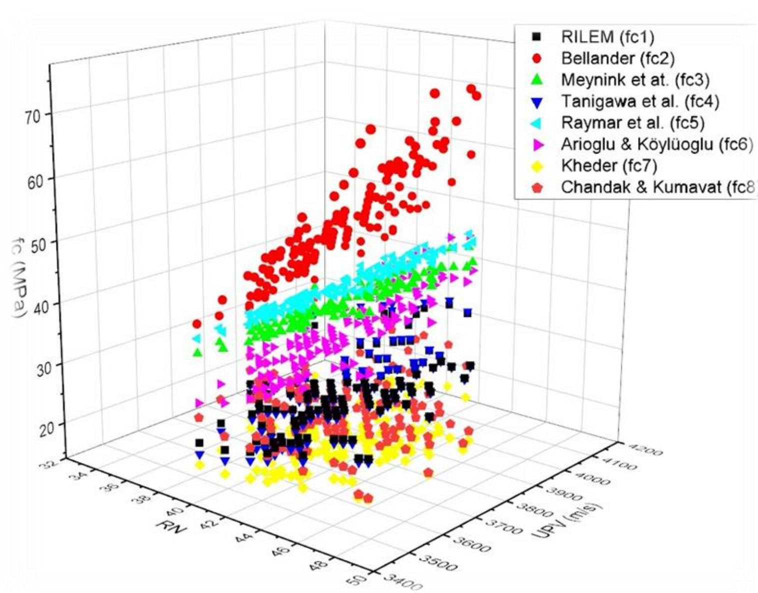

Figure 5*. General distribution of the results obtained from the application of selected SonReb models*

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To determine the influence on fc, the results were correlated independently by combining the RN and the UPV obtained with the calculated fc. The results obtained are shown in (Figure 4), (Figure 5), (Figure 6), (Figure 7), (Figure 8), (Figure 9), (Figure 10) and (Figure 11). For the construction of the graphs, the data were organized from the statistical processing, so that all the models had the same population of data.

The analysis of the behavior of the RN and UPV variables with respect to the calculated fc shows that in the models where there is a coherent correlation for both pairs of variables (RN vs fc, UPV vs fc) (Figure 6), (Figure 7), (Figure 8) and (Figure 9), the calculated fc obtained tends to be closer to the real value. For the cases of the models proposed by Bellander, Meynink et al., Raymar et al. and Kheder (Figure 7), (Figure 8), (Figure 10) and (Figure 12) respectively, although they show a very good correlation between the RN vs fc, with respect to the UPV there does not seem to be an influence of this variable on the fc, for which the fc obtained greatly differ from the reference value of 27.0 MPa. Perhaps this is the reason why the differences with respect to the reference value were greater than 20% for all cases. An interesting result was obtained from the (Chandak & Kumavat model (Figure 13), where the RN and UPV relationships are opposed with respect to the fc. That the error obtained was less than 15% may be associated with the fact that although the correlations are contrary, there is an actual influence of the RN and the UPV on the fc.

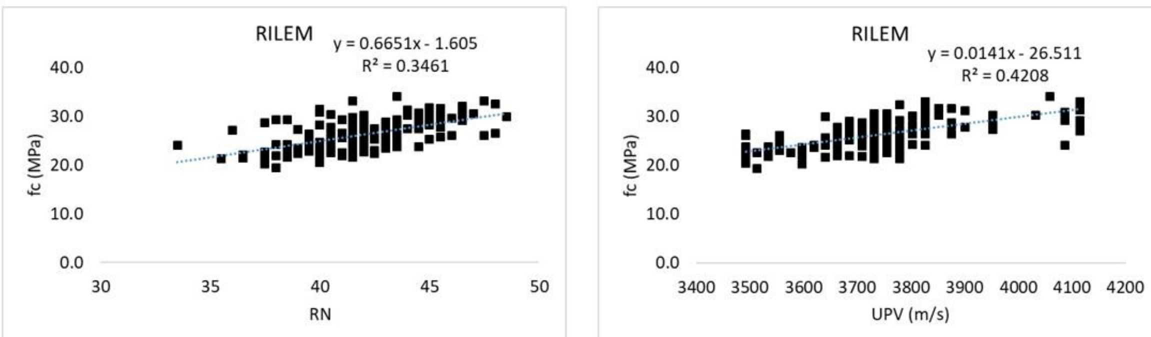

***Figure 6**. Correlation results obtained for RILEM model*

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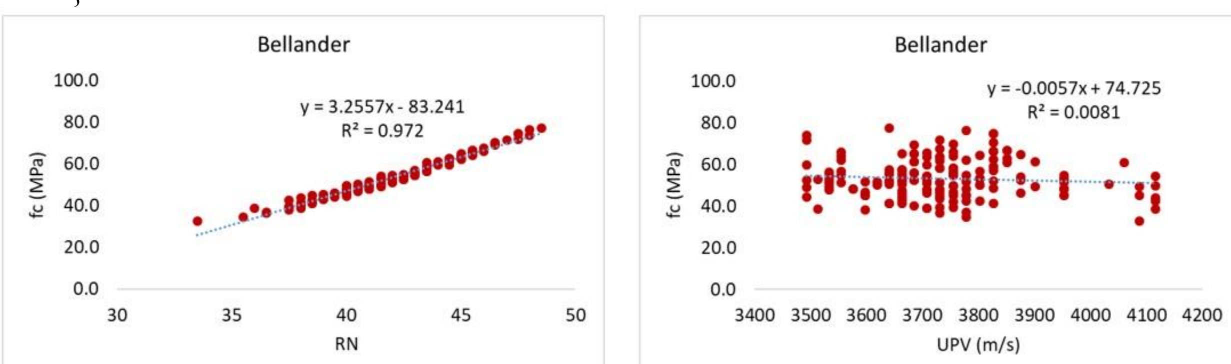

***Figure 7.** Correlation results obtained for Bellander model*

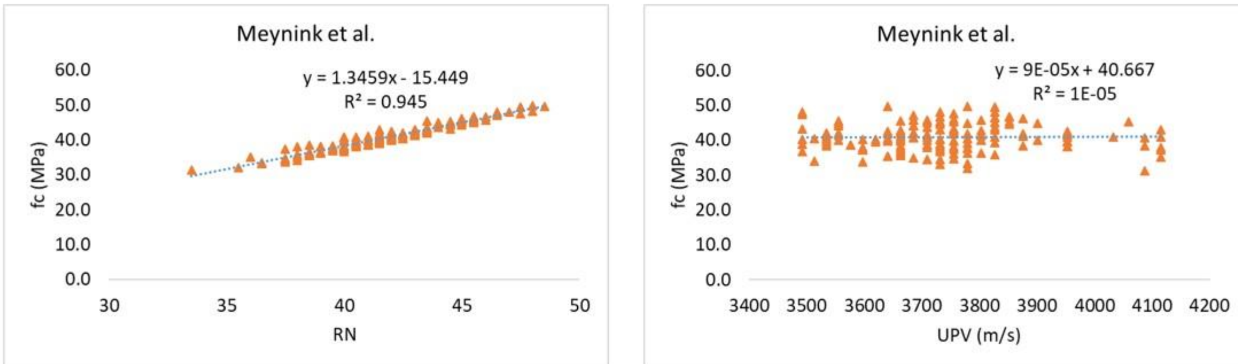

Figure 8. *Correlation results obtained for Meynink et al. model*

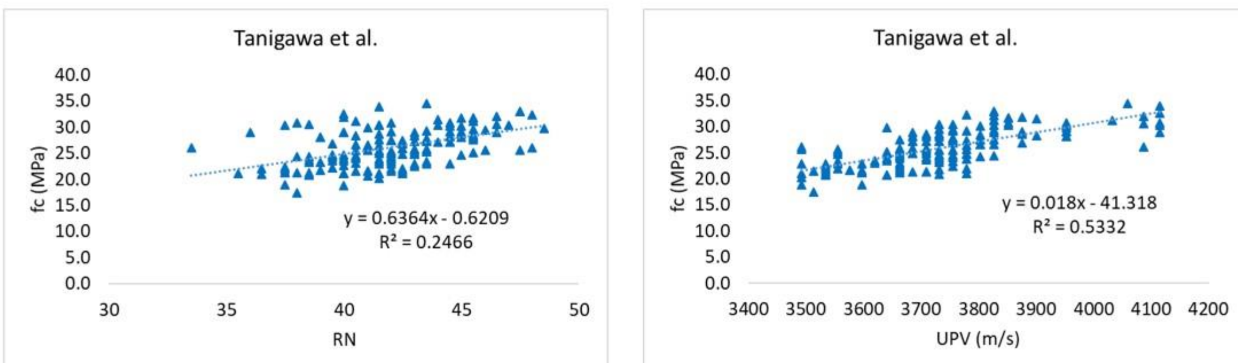

Figure 9. *Correlation results obtained for Tanigawa et al. model*

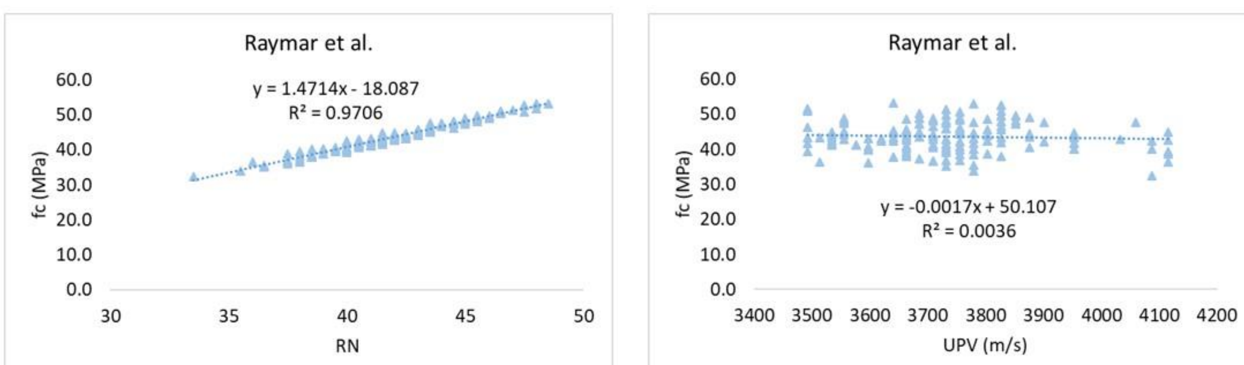

Figure 10. *Correlation results obtained for Raymar et al. model*

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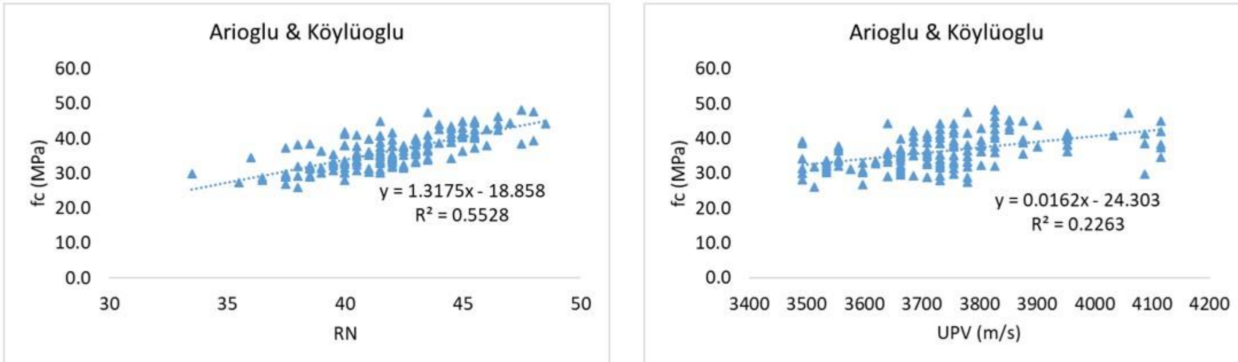

Figure 11. *Correlation results obtained for Arioglu & Köylüoglu model*

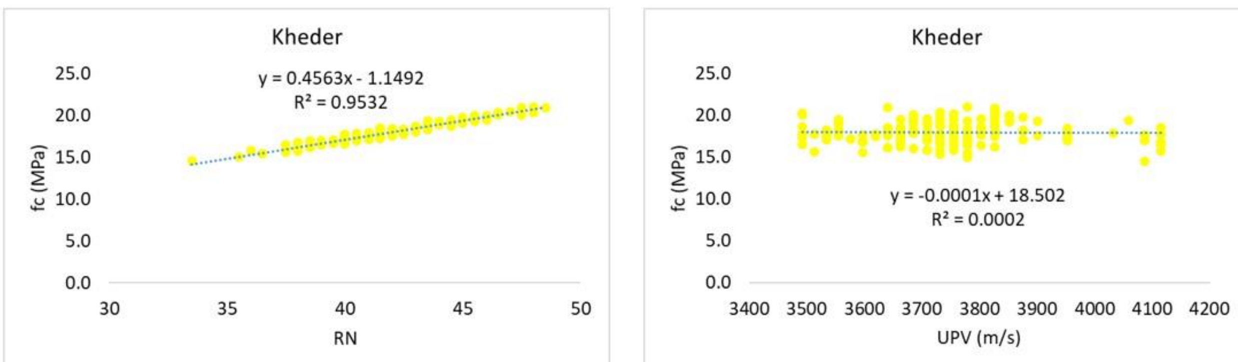

Figure 12. *Correlation results obtained for Kheder model*

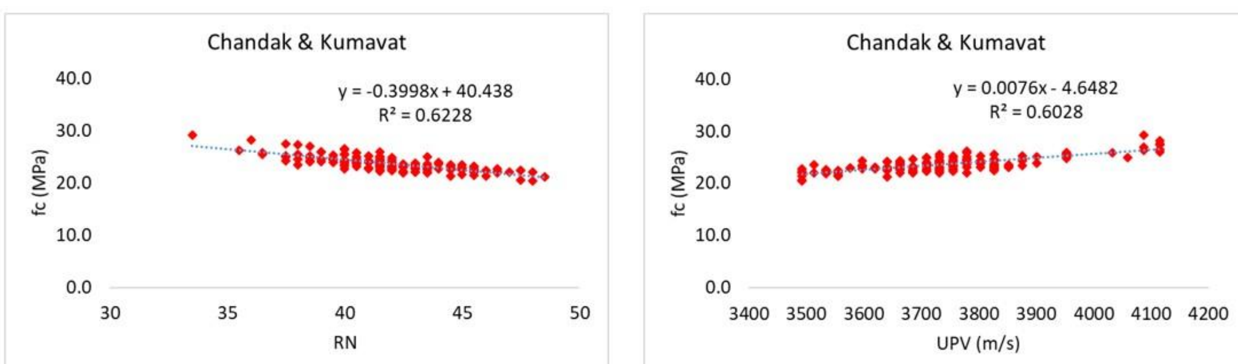

Figure 13. *Correlation results obtained for Chandak & Kumavat model*

5. Conclusions

Based on the results obtained from de application of the different SonReb models used for the estimation of the compressive strength of concrete produce with Cuban ordinary Portland Cement P-35 (Type 1) and domestic aggregates, it was demonstrated that models proposed by RILEM and Tanigawa et al. exhibit results closer to the reference value with respect to the rest of the models, for a coefficient of variation below 15% in both cases.

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Statistical analysis reflected that for these models, there is a high correlation and similar behaviors between the rebound hammer and the ultrasonic pulse speed with respect to compressive strength, compared to the rest of the models used.

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