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Statistical Equations to Estimate the In-situ Concrete Compressive Strength from Non-destructive Tests

Dr. Ahmed Faleh Al-Bayati
Lecturer
College of Engineering -AL-Nahrain University
Email: ahmed_lbyt@hotmail.com

ABSTRACT

The aim of this study is to propose reliable empirical equations to estimate the in-situ concrete compressive strength from non-destructive tests. Three equations were proposed: the first equation considers the number of rebound hummer only, the second equation considers the ultrasonic pulse velocity only, and the third equation combines the number of rebound hummer and the ultrasonic pulse velocity. The proposed equations were derived from non-linear regression analysis and they were calibrated with the test results of 372 concrete specimens compiled from literature. The performance of the proposed equations was tested by comparing their strength estimations with those of related existing equations from literature. Comparisons revealed that the proposed ultrasonic pulse velocity and combined equations achieved better agreements with the test results than the related existing equations, whereas the proposed and the existing rebound hummer equations were inconsistent.

Keywords: Concrete compressive strength, non-destructive tests, rebound hummer test, ultrasonic pulse velocity, combined method, assessment of existing structure.

معادلات تجريبية لحساب مقاومة انضغاط الخرسانة الموقعية من خلال الفحوصات اللأتلافية

د. احمد فالح البياتي
مدرس
كلية الهندسة-جامعة النهرين

الخلاصة

تهدف هذه الدراسة الى ايجاد معادلات تجريبية موثوقة لحساب مقاومة انضغاط الخرسانة الحقلية من خلال الفحوصات اللااتلافية. ثلاث معادلات أقترحت في هذه الدراسة: المعادلة المقترحة الاولى تعتمد على رقم الارتاد في فحص المطرقة، المعادلة الثانية تعتمد على سرعة الامواج فوق الصوتية، المعادلة الثالثة تدمج بين رقم الارتداد في فحص المطرقة و سرعة الامواج فوق الصوتية في حساب مقاومة الانضغاط للخرسانة. تم تطوير هذه المعادلات باستخدام التحليل اللاخطي والنتائج المختبرية الخاصة ب 372 نموذج من البحوث السابقة. تمت مقارنة نتائج حساب مقاومة الانضغاط بواسطة المعادلات المقترحة مع المعادلات المقترحة مسبقا للتأكد من دقة المعادلات المقترحة. اظهرت المقارنات ان المعادلة المدمجة وتلك التي تعتمد على سرعة الامواج فوق الصوتية المقترحتين في هذا البحث اكثر دقة في حساب مقاومة الانضغاط للخرسانة من المعادلات المقترحة مسبقا المناظره لهما. فيما

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*Corresponding author

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كانت حسابات مقاومة الانضغاط للخرسانة بواسطة المعادلة المقترحة في هذا البحث التي تعتمد على رقم الارتداد في فحص المطرقة والمعادلات المقترحة مسبقا المناظرة لها غير دقيقة.

الكلمات المفتاحية: مقاومة انضغاط الخرسانة، فحوصات لا اتلافية، فحص المطرقة، فحص الامواج فوق الصوتية، المعادلة المدمجة، تقييم المنشأت المشيدة.

1. INTRODUCTION

Some existing structures experience modifications instead of demolishing and reconstruction either to lengthen their life or to deal with a new assigned function. In such cases, structural assessment is required to determine the capacity of structures and to examine their ability in accommodating the new imposed loadings. The assessment of any structure requires information about of the geometry of structural members, the loadings criteria, and the mechanical properties of materials. The determination of compressive strength of in-situ concrete can be regarded as the key element in the assessment of existing reinforced concrete structures.

Compression destructive test on concrete cores drilled out from existing structures is considered the most reliable method used to evaluate the compressive strength of in-situ concrete. In addition, cores can be used to determine density, water absorptions, tensile strength, and concrete expansion, **Bungey et al., 2006**. The guideline of cores sampling and testing have been included in various standards, **214.4R-03, 2013; ASTM C42/C 42M, 2008**. Despite of these benefits, this method suffers from certain drawbacks. Along with being relatively expensive and laborious, it might not be suitable to inspect all structural members either due to inconvenient accessibility or to avoid jeopardizing the integrity and durability of the structural members, especially for those in service, **Vasanelli et al., 2017; Alwash et al., 2016**. As a results, the number of cores would be limited and they might not cover the entire structure leading to inconclusive results, **Alwash et al., 2015**.

To overcome the deficiencies associated with the usage of drilled cores, non-destructive tests are employed to assess the compressive strength of in-situ concrete. Rebound hammer and ultrasonic pulse velocity are considered the most popular methods used in practice, **Malhotra and Carino, 2002**. The assessment of concrete strength, using these methods, is derived from predictive equations furnished with devices usually calibrated with limited database, **Vasanelli et al., 2017; Breysse and Martínez-Fernández, 2013; Proceq 2006**. The use of such equations is therefore questionable when they applied to estimate the compressive strength of various types of concrete made from different mixtures and cured under various conditions, **Breysse and Martínez-Fernández, 2013**.

The American standard, **ACI 228.1R-13, 2013**, and European standard, **EN 13791, 2007**, require that non-destructive tests need to be used in company with destructive core tests. The procedure recommended by these standards involves establishing a specific regression equation that combines the number of rebound hummer and the ultrasonic pulse velocity. This equation has to be validated by the test results of cores taken from the same location, where non-destructive tests conducted. To establish such equation, the American standard and the European standard (Alternative 1 approach) require the results of no less than twelve cores and eighteen cores, respectively, to be calibrated with the results of non-destructive tests. European standard (Alternative approach 2) allows to use the results of a smaller numbers of cores (nine cores) to modify an existing regression equation.

It is believed that the number of cores imposed by the aforementioned standards is somewhat impractical and considerably high, **Vasanelli et al., 2017; Alwash et al., 2016; Breysse and Martínez-Fernández, 2013**. Practitioners are therefore have a tendency to ignore such limitations and carry on the in-situ concrete assessment using either predictive equations suggested by devices' producers or existing strength equation calibrated with a smaller number of cores than that required by such standards, **Ali-Benyahia et al, 2017**; **Alwash et al., 2015; Breysse, 2013**.

Although various equations have been derived to estimate the in-situ concrete strength, these equations are usually calibrated with limited range of datasets at the time of derivation. They are generally inconsistent and scattered when they applied to estimate the concrete strength constructed from different materials due to concrete variability, **Vasanelli et al., 2017**.

The use of rebound hammer and ultrasonic pulse velocity in practice is disadvantaged by the lack of consistent strength equations. Therefore, there is a necessity to form general strength equations that is calibrated with wide range of datasets and correlate well with a large number of test specimens.

To that end, three statistical equations based on non-linear regression analysis are proposed to improve the compressive strength estimations of in-situ concrete. The first equation is a function of the numbers of rebound hummer, the second equation is a function of the ultrasonic pulse velocity, and the third equation is a function of both the number of rebound hammer and the ultrasonic pulse velocity. The proposed equations are calibrated with 372 test datasets compiled from previous experimental studies. The performance of the proposed equations is examined by comparing their strength estimations with those of related existing equations.

2. REBOUND HUMMER

The Schmidt rebound hammer is a simple inexpensive method that used to evaluate the hardness surface of concrete. As shown in **Fig 1**, the device consists of a plunger, a hummer mass, a spring, and a sliding indicator, **Malhotra and Carino, 2002**. When the hummer is pushed against the concrete surface, the plunger generates an impact on the surface. The rebound number is simply the measured distance by the sliding indicator **Malhotra and Carino, 2002**.

The relationship between the rebound number and the concrete strength is basically derived from the wave propagation mechanism, **Akashi and Amasaki, 1984**. In which, the ratio of the compressive wave induced by the generated impact on the concrete surface and the reflected compression wave associated with the reaction force, which could be empirically related to the concrete compressive strength.

3. ULTRASONIC PULSE VELOCITY

The principle of this method is to measure the velocity of compression waves through a solid medium, refer to **Fig 2**, **Malhotra and Carino, 2002**. As expressed by the following equation, the velocity of compression waves, V, is a function of elastic properties of the medium, **Malhotra and Carino, 2002**:

$$V = \sqrt{\frac{EK}{\rho}} \tag{1}$$

Where, E is the dynamic modulus of elasticity of the medium, $K = {(1-\mu)}\Big/{(1+\mu)(1-2\mu)}$, μ is the dynamic Poisson's ratio, and ρ is the mass density of the medium. Following this law, a relationship could be established between the velocity measurement and the concrete compressive strength, in association with the existing relationship between the concrete compressive strength and the concrete modulus of elasticity, **Pascale and Di Leo, 1984; Pascale et al., 2003**.

4. DATASETS

The measurements of rebound hummer and ultrasonic pulse velocity were observed to be affected by the mechanical properties of concrete. The numbers of the rebound hummer was observed to be affected by the smoothness of concrete surface, concrete moisture state, and concrete carbonations, **Breysse, 2012; Nobile, 2014; Qasrawi, 2000**. And, the measurement of ultrasonic pulse velocity was observed to be affected by other mechanical properties such as the type of cement and aggregates, the proportions of concrete mixture, the existence of micro-cracks and steel reinforcements, and the age of concrete, **Breysse, 2012; Nobile 2014; Qasrawi, 2000**.

The majority of previously developed equations, however, do not consider the mechanical properties of concrete such as the type of material, the mix design, and the age. They rely only upon the measurements of non-destructive tests. This is because of the high variability of concrete and the absence of accurate information about the materials properties especially for existing structures, **Qasrawi, 2000; Nobile 2014; Amini et al., 2016**. General strength equations, however, still can be established and the influence of the factors described above can be taken into account indirectly if the proposed equations were to be calibrated with a large number of specimens constructed from various mixtures and ingredients, cured in various conditions, and tested at various ages.

Thus, a total of 372 datasets of concrete specimens tested by Schmidt rebound hammer, ultrasonic pulse velocity, and axial crushed compressive strength were compiled from literature. Specimens were constructed using different mixtures, from various types of cement and aggregates from different countries, subjected to different curing conditions, and tested at various ages. Details of concrete properties and test programs are not described here, and only the salient points are summarized in **Table 1.**

Specimens considered were cubes, cylinder, beams, columns, and foundations from various test programs. The ultrasonic pulse velocity, UPV, of the compiled specimens ranged between 2.2 km/s and 5.4 km/s, the rebound number, RN, from 20 to 53.5, and the crushed cylinder compressive strength, f_c, from 16.3 MPa to 48.7 MPa. Statistics of the datasets are presented in Table 1.

It is important to note that the crushed concrete strength is converted from a cube value, f_{cu}, to a cylinder one using the following equation, **Neville, 2011**:

$$f_c = 0.8\, f_{cu} \qquad \text{Eq. (2)}$$

5. EXISTING EQUATIONS

A critical review about the selected existing equations revealed that these equations are generally varied in terms of their mathematical nature and the considered variables. Equations are either linear, non-linear, or exponential. Some equations are single variable consider either the numbers of rebound hummer or the ultrasonic pulse velocity, others consider the combined measurements of rebound hummer and ultrasonic pulse velocity. **Table 2** lists the selected existing equations from literature.

6. PROPOSED EQUATIONS

The following equations are derived from non-linear regression analysis conducted using **SPSS Statistics 22, 2016**, to estimate the in-situ concrete compressive strength from non-destructive tests. The proposed equations are calibrated with the test results of 372 specimens compiled from literature. The first equation is a single variable that considers the numbers of rebound hummer,

RN, in the estimation of concrete compressive strength: $f_{c\,pred} = 16.9 * RN^{0.13} + 3.6 * 10^{-9} * RN^{5.6}$ Eq. (3)

The second equation is also a single variable which considers the ultrasonic pulse velocity, UPV, in the estimation of concrete compressive strength:

$f_{c\,pred} = 15.9 * UPV^{0.26} + 9 * 10^{-5} * UPV^{7.25}$ Eq. (4)

The third equation combines the number of rebound hummer, RN, and the ultrasonic pulse velocity, UPV, as expressed as follows:

$f_{c\,pred} = 4.41 * RN^{0.46} + 21 * 10^{-5} * UPV^{6.8}$ Eq. (5)

It is important to note that the estimated concrete compressive strength, $f_{c\,pred}$, represents a cylinder concrete strength in MPa. The ultrasonic pulse velocity, UPV, of Eq. (4) and (5) in km/s.

7. VALIDATION OF THE PROPOSED EQUATIONS

Figures 3 to 5 show the proposed equations (solid line), their correlation coefficient (R), and the test results of 372 specimens from literature. As can be inferred from Figure 3, the proposed rebound hummer equation, Eq. (3), provided inconsistent strength estimations with a correlation coefficient (R) of 0.39. In contrast, the proposed ultrasonic pulse velocity equation and the combined equation provided consistent strength estimations (refer to Figures 4 and 5), with correlation coefficient (R) of 0.78 and 0.81, respectively. The higher correlation coefficient of Eq. (5) as compared with that of Eq. (4) clearly shows the improvement of concrete strength estimations when the combined methods used together.

However, the correlation coefficient (R) alone is not always a satisfactory proof of the accuracy of a proposed equation, **Montgomery and Runger, 1998**. Hence, further comparisons are carried out between the estimated strength by the proposed equations and available experimental results, see Figure 6 to 8. In these figures, the line of perfect equality (diagonal solid line) and the 90% prediction interval (the two dashed lines) are included to examine the accuracy of the proposed equations. Figure 6 proves again that Eq. (3) is inconsistent and widely scattered, as the majority of the estimated strength to test ratios are falling out of the upper and the lower bounds of the 90% prediction interval. Unlike Eq. (3), the proposed equations, Eq. (4) and Eq. (5), have correlated well with the test results. As can be seen from Figures 7 and 8 that, the majority of strength estimated strength to test ratios fall within the upper and the lower bounds of the 90% prediction interval. The lower standard deviation of Eq. (5), as compared with that of Eq. (4), clearly shows the improvement of concrete strength estimations when the combined rebound hummer and ultrasonic pulse velocity measurements used together.

8. COMPARISONS BETWEEN THE PROPOSED AND THE EXISTING EQUATIONS

A. Rebound hummer equations

Table 3 compares the mean, the standard deviation, the correlation coefficient, and the root mean square error of the proposed equation, Eq. (3), and the existing rebound hummer equations, **Raouf, 1986; Qasrawi, 2000; Nash't et al., 2005; Hobbs et al., 2007**. As can be inferred from this table that all equations provided inconsistent strength estimations. The equations of **Qasrawi, 2000** and **Nash't et al., 2005** underestimated the concrete strength and those of **Raouf, 1986** and **Hobbs et al., 2007** overestimated the concrete strength.

This is hardly surprising due to the high variations in rebound numbers that reflect the hardness of concrete surface only, which would consequently lead to inconsistent strength estimations, **Pucinotti, 2015; Qasrawi, 2000; Malhotra and Carino, 2002**.

B. Ultrasonic pulse velocity equations

Table 4 compares the mean, the standard deviation, the correlation coefficient, and the root mean square error of the proposed equation, Eq. (4), and the existing ultrasonic pulse velocity equations, **Raouf, 1986; Qasrawi, 2000; Nash't et al., 2005; Hobbs et al., 2007**. Comparisons revealed that the proposed equation achieved better agreement with the test results than existing equations. This is attributed to the wide range dataset employed in the calibration of the proposed equation as compared with the existing equations.

The equations of **Raouf, 1986** and **Nash't et al., 2005** underestimated the concrete strength and those of **Qasrawi, 2000** and **Hobbs et al., 2007** overestimated the concrete strength.

Further comparisons between the strength estimations provided by the rebound hummer equations (Table 3) and those provided by the ultrasonic pulse velocity equations (Table 4) showed that the ultrasonic pulse velocity method is more efficient in the strength estimations than the rebound hummer method, **Pucinotti, 2015; Qasrawi, 2000**.

C. Combined rebound hummer and ultrasonic pulse velocity equations

Table 5 compares the mean, the standard deviation, the correlation coefficient, and the root mean square error of the proposed equation, Eq. (5), and the existing combined equations. It appears that the proposed equation provided better strength estimations than the existing equations. Again, this is because of the wide range dataset used in the calibrations with the proposed equation.

The equation of **Raouf, 1986** provided consistent strength estimations, while those of **Nash't et al., 2005** and **Amini et al., 2016** underestimated the concrete compressive strength and those of **Giacchetti and Lacquaniti, 1980; Gasparik, 1992; Di Leo and Pascale, 1994; and Hobbs et al., 2007**, overestimated the concrete compressive strength.

By comparing Tables 4, 5, and 6, the correlations with the test results are in general improved using the combined equations. This would be expected because when rebound hummer and ultrasonic pulse velocity methods are combined together, their shortcomings are reduced to minimum, as the rebound hummer method provides information of the concrete surface and the ultrasonic pulse velocity method provides insight information about the concrete properties, **Huang et al., 2011; Nobile, 2014; Amini et al., 2016**.

9. Summary and conclusions

Three equations were derived from non-linear regression analysis to estimate the in-situ concrete compressive strength from non-destructive tests. The proposed equations were calibrated with the test results of 372 concrete specimens from literature. The first equation, Eq. (3), considers the numbers of rebound hummer only, the second equation, Eq. (4), considers the ultrasonic pulse velocity only, and the third equation, Eq. (5), combines the numbers of rebound hummer and the ultrasonic pulse velocity. The following conclusions are drawn from the present study:

1. The use of the proposed combined equation, Eq. (5), significantly improved the concrete strength estimations in comparisons with the proposed rebound hummer equation, Eq. (3), and the proposed ultrasonic pulse velocity equation, Eq. (4). This clearly shows that the use of combined equations provide a more consistent and reliable strength estimations than the single variable equations.

2. Despite of being less accurate than the combined methods in terms of concrete strength estimation, comparisons with the test results revealed that the use of ultrasonic pulse velocity method alone is more efficient than the use of rebound hummer method alone in terms of concrete strength estimations.
3. Comparisons with the test results indicated that, the use of rebound method alone is not appropriate due to the high variability of concrete, which would consequently lead to inconsistent strength estimations.
4. Statistical comparisons between the estimated strengths provided by the proposed equations and those provided by the related existing equations in terms of mean, standard deviation, correlation coefficient, and root mean square error showed that the proposed equations achieved better agreements with the test results than the existing ones.
5. The proposed combined equation is recommended to be used in daily practice. It achieved a mean of 1.00, the highest correlation coefficient of 0.81, and the least root mean square error of 4.46 MPa.

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Table 1. Summary of the datasets used in this research.

Source	No. of specimens	Type of specimen	Age of test (days)	UPV (km/s)	Rn (%)	f_c (MPa)
Cianfrone and Facaoaru, 1979	57	Cubes	1,2,3,7,28	4.8-5.4	25.0-45.0	22.4-48.6[a]
Knaze and Beno, 1984	45	Cubes	28,32	4.0-4.4	26.7-40.8	19.2-28.4[b]
Na et al., 2009	20	Cubes and cylinder	3,7,1428,90,180,365	3.9-4.8	20.7-46.4	19.5-47.6[c]
Domingo and Hirose, 2009	10	Cubes	1,3,7,14	4.0-4.8	25.0-45.0	20.3-48.7[a]
Hannachi and Guetteche, 2012	10	Beams and columns	28	3.9-4.2	26.0-30.0	25.5-36.0[d]
Fawzi et al., 2013	24	beams, columns, slab and foundation	28	4.3-4.8	33.0-44.0	21.6-33.8[e]
Nobile and Bonagura, 2013	9	Beams and columns of an existing building	-	2.9-3.5	32.0-41.0	17.8-29.3[d]
Jain et al., 2013	32	Cubes	7,28,56	4.5-5.2	32.7-53.5	22.3-47.5a
Osman et al., 2014	48	Cubes	28	4.5-5.4	25.6-33.3	25.4-40.3a
Nobile, 2014	12	Beams and columns of an existing building	-	2.8-3.7	32.0-45.0	17.5-36.8d
Mulik et al., 2015	12	Cubes	28	4.0-4.3	29.2-39.8	20.5-32.2[a]
Masi et al., 2016	14	Beams and columns of an existing building	-	2.2-4.4	20.0-43.0	16.3-35.3[d]
Rashid and Waqas, 2017	24	Cubes	7, 28, 56	4.2-4.9	31.0-39.0	21-41.8[a]
Kumar and Kumar, 2015	55	Cubes	7 , 28, 90	4.2-4.7	32.7-48.5	22.0-38.0[a]
Total No.	372		Minimum	2.2	20.0	16.3
			Maximum	5.4	53.5	48.7
			Mean	4.5	35.8	30.8
			Mode	4.5	37.0	25.6
			Standard deviation	0.5	5.9	7.3

a The destructive tests were conducted on cubes with 150 mm side length and the author has converted the concrete compressive strength from cube to equivalent cylinder strength using Eq. (2).

b The destructive tests were conducted on cubes with 200 mm side length and the author has converted the concrete compressive strength from cube to equivalent cylinder strength using Eq. (2).

c the source has reported the standard cylinder concrete compressive strength.

d The source has converted the concrete compressive strength from core to equivalent standard cylinder strength.

e The source has reported the concrete strength of the specimens in terms of 150 mm cube strength and the author has converted the concrete strength from cube to equivalent cylinder strength using Eq. (2).

Table 2. Selected equations from literature .

Source	Variables (units)	Equations
Raouf, 1984	RN (No.)	$f_{cu} = 0.74\, RN^{1.12}$
Qasrawi, 2000	RN (No.)	$f_{cu} = 1.353\, RN - 17.393$
Nash't et al., 2005	RN (No.)	$f_{cu} = 0.788\, RN^{1.03}$
Hobbs et al., 2007	RN (No.)	$f_{cu} = 2.168\, RN - 27.747$
Raouf, 1984	UPV (km/sec)	$f_{cu} = 2.8\, e^{0.53\, UPV}$
Qasrawi, 2000	UPV (km/sec)	$f_{cu} = 36.72\, UPV - 129.077$
Nash't et al., 2005	UPV (km/sec)	$f_{cu} = 1.19\, e^{0.715\, UPV}$
Hobbs et al., 2007	UPV (km/sec)	$f_{cu} = 12.289\, UPV^2 - 49.024\, UPV + 24.271$
Giacchetti and Lacquaniti, 1980	RN (No.) and UPV (km/sec)	$f_c = 7.696\ 10^{-11} RN^{1.4} UPV^{2.6}\, *$
Raouf, 1984	RN (No.) and UPV (km/sec)	$f_{cu} = 0.93\, RN^{0.63} e^{0.314\, UPV}$
Gasparik, 1992	RN (No.) and UPV (km/sec)	$f_c = 0.0286\, RN^{1.246} UPV^{1.85}\, *$
Di Leo and Pascale, 1994	RN (No.) and UPV (m/sec)	$f_c = 1.2\ 10^{-9} RN^{1.058} UPV^{2.446}\, *$
Nash't et al., 2005	RN (No.) and UPV (km/sec)	$f_{cu} = 0.356\, RN^{0.866} e^{0.302\, UPV}$
Hobbs et al., 2007	RN (No.) and UPV (km/sec)	$f_{cu} = 173.033 - 4.069\, UPV^2 + 57.693\, UPV + 1.307\ RN^2$
Amini et al., 2016	RN (No.) and UPV (km/sec)	$f_c = 0.10983 + 0.00157\, RN - 0.79315\, UPV - 0.00002\ RN^2 - 1.29261 UPV^2$

* As reported by **Nobel, 2014**.

Table 3. Statistical results of the proposed and existing rebound hummer equations.

Source	Mean ($f_{c\,pred}/f_{c\,test}$)	Standard deviation ($f_{c\,pred}/f_{c\,test}$)	Correlation Coefficient (R)	Root mean square error, RMSE (MPa)
Raouf, 1984	1.11	0.28	0.35	9.84
Qasrawi, 2000	0.84	0.25	0.35	12.28
Nash't et al., 2005	0.85	0.21	0.35	11.24
Hobbs et al., 2007	1.34	0.40	0.35	17.25
Proposed Eq. (3)	1.00	0.22	0.39	30.68

Table 4. Statistical results of the proposed and existing ultrasonic pulse velocity equations.

Source	Mean ($f_{c\,pred}/f_{c\,test}$)	Standard deviation ($f_{c\,pred}/f_{c\,test}$)	Correlation Coefficient (R)	Root mean square error, RMSE (MPa)
Raouf, 1984	0.83	0.15	0.72	9.20
Qasrawi, 2000	1.02	0.24	0.74	5.66
Nash't et al., 2005	0.82	0.18	0.77	9.56
Hobbs et al., 2007	1.50	0.44	0.72	18.92
Proposed Eq. (4)	0.99	0.15	0.78	4.79

Table 5. Statistical results of the proposed and existing combined equations.

Source	Mean $(f_{c\,pred}/f_{c\,test})$	Standard deviation $(f_{c\,pred}/f_{c\,test})$	Correlation Coefficient (R)	Root mean square error, RMSE (MPa)
Giacchetti and Lacquaniti, 1980	1.22	0.33	0.74	12.66
Raouf, 1984	0.96	0.16	0.76	6.37
Gasparik,1992	1.33	0.31	0.71	13.52
Di Leo and Pascale, 1994	1.29	0.35	0.94	16.67
Nash't et al., 2005	0.99	0.42	0.17	14.6
Hobbs et al., 2007	1.31	0.31	0.68	15.3
Amini et al., 2016	0.76	0.14	0.74	9.12
Proposed Eq. (5)	1.00	0.14	0.81	4.46

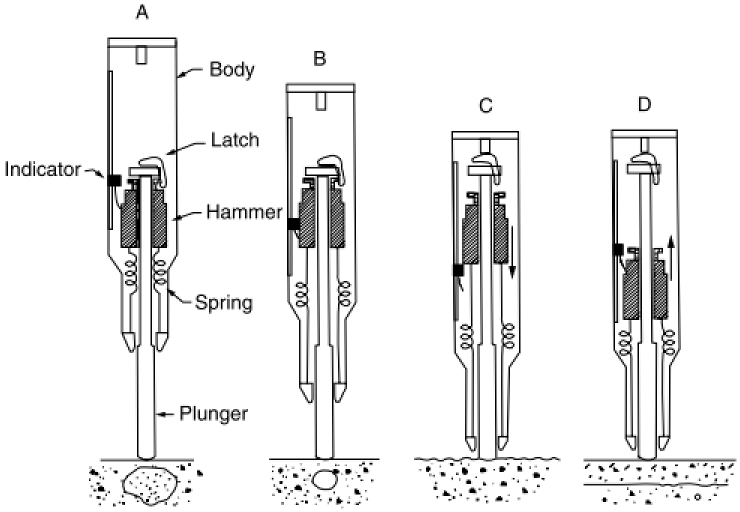

Figure 1. Schematic outline of the rebound hummer test, after **Malhotra and Carino, 2002**

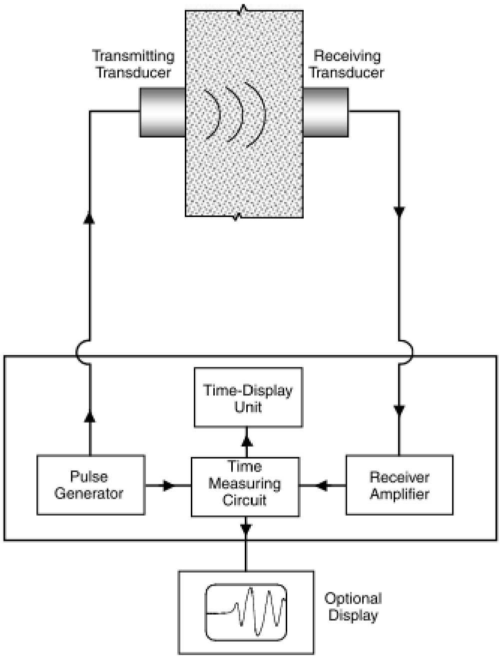

Figure 2. Schematic outline of the ultrasonic pulse velocity test, after **Malhotra and Carino, 2002.**

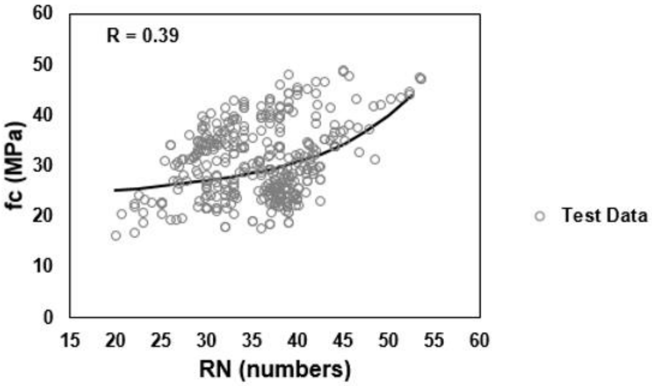

Figure 3. Correlations of the estimated concrete compressive strength using Eq. (3) and the numbers of rebound hummer.

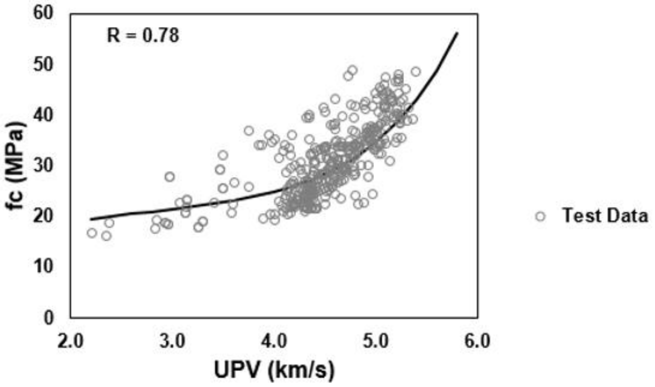

Figure 4. Correlations of the estimated concrete compressive strength using Eq. (4) and the ultrasonic pulse velocity.

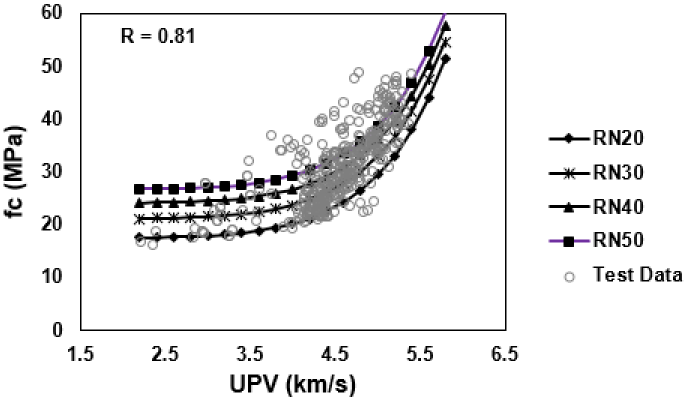

Figure 5. Correlations of the estimated concrete compressive strength using Eq. (5), the ultrasonic pulse velocity, and the numbers of rebound hummer.

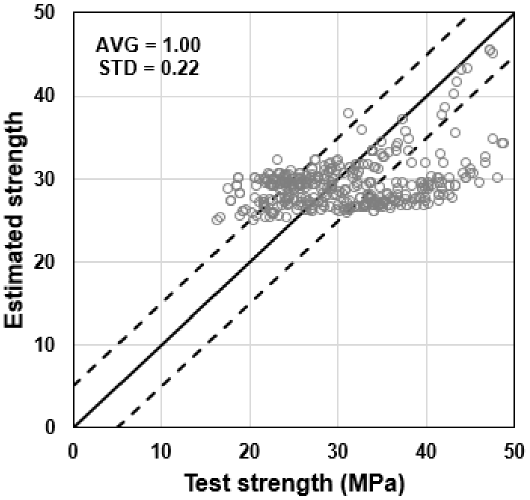

Figure 6. Strength estimations using Eq. (3).

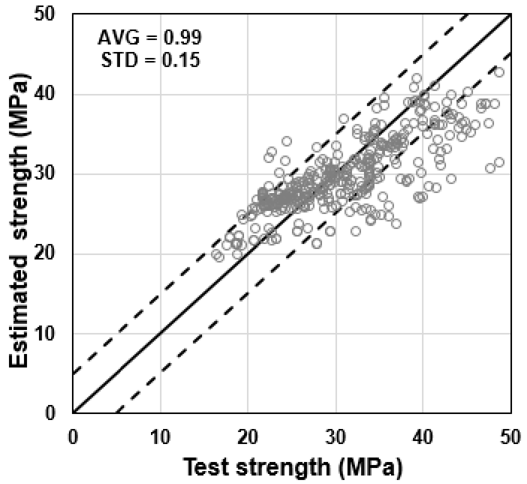

Figure 7. Strength estimations using Eq. (4).

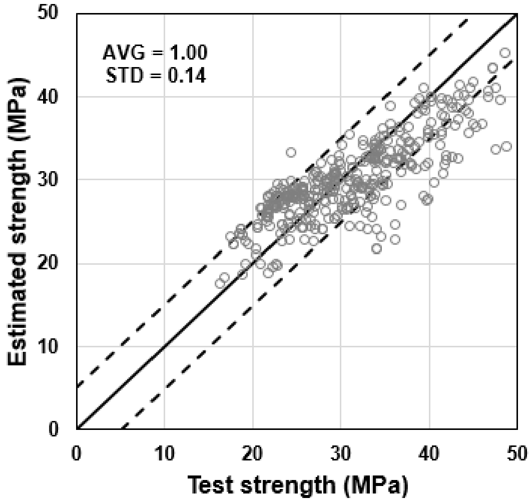

Figure 8. Strength estimations using Eq. (5).