Correlation Curves to Characterize Concretes Used in Rio de Janeiro by Means of Non-destructive Tests

Curvas de Correlação para Caracterizar Concretos Usados no Rio de Janeiro por Meio de Ensaios Não Destrutivos

M. D. MACHADO [a]
mauriciodornellas@hotmail.com

L. C. D. SHEHATA [b]
lidiashehata@vm.uff.br

I. A. E. M. SHEHATA [c]
ibrahim@coc.ufrj.br

Abstract

Non-destructive tests give information about the properties of the concrete of a structure, but the reliability of the evaluation of those properties depends on the experience of the professional that carries out the tests and the curves employed to correlate the measured values with the properties of the investigated concrete. The main objective of this study was to supply engineers with correlation curves that make it possible to evaluate, by using non-destructive test results, the compressive strength and the modulus of elasticity of ready-mixed concretes used in Rio de Janeiro. Test specimens cast with concretes used in several constructions and supplied by different ready-mixed concrete producers were tested. These concretes had, in general, nominal fck value of 25 MPa or 30 MPa. Aiming to include concretes with strength varying within a wider range and made with the two types of typical coarse aggregates of Rio de Janeiro, test specimens cast in the laboratories of two ready-mixed concrete producers were tested. In these concretes, the water-cement ratio (0.40 to 0.60) and the petrographic characteristic of the coarse aggregate were varied. Compressive strength and modulus of elasticity tests, ultrasonic pulse velocity, rebound hammer and penetration resistance tests were carried out, at the ages of 3, 7, 14, 28 and 90 days. The correlation curves obtained from the analysis of the results of all those tests are presented here. When only one non-destructive test was used, the rebound hammer was the one that led to the best estimation of compressive strength and the combination of that test with the penetration resistance test improved the accuracy of the evaluation. If modulus of elasticity tests cannot be carried out, the ultrasonic pulse velocity test can be an interesting option to evaluate that property.

Keywords: correlation curves, nondestrutive tests, ready-mixed concrete

Resumo

Os ensaios não destrutivos fornecem informações quanto às propriedades do concreto das estruturas, mas a confiabilidade da avaliação dessas propriedades depende da experiência do profissional que realiza esses ensaios e das curvas empregadas para correlacionar as grandezas medidas nos ensaios com as propriedades do concreto investigado. Este estudo visou prover os engenheiros de curvas de correlação que os possibilitem estimar, por meio da utilização de ensaios não destrutivos, a resistência à compressão e o módulo de elasticidade dos concretos dosados em central utilizados no Rio de Janeiro. Foram ensaiados corpos-de-prova moldados com concretos usados em diversas obras, fornecidos por diferentes concreteiras. Esses concretos tinham, em geral, fck nominal de 25 MPa ou 30 MPa. Objetivando englobar concretos com resistências mais variadas e os dois tipos de agregados graúdos típicos do Rio de Janeiro, foram ensaiados corpos-de-prova moldados nos laboratórios de dois grupos de concreteiras. Nestes concretos, variaram-se a relação água-cimento (0,40 a 0,60) e a característica petrográfica do agregado graúdo. Foram realizados ensaios de resistência à compressão e de módulo de elasticidade, de velocidade de propagação de ondas ultra-sônicas, de esclerometria e de penetração de pinos, em concretos com idades de 3, 7, 14, 28 e 90 dias. Aqui são apresentadas as curvas de correlação obtidas a partir da análise dos resultados de todos esses ensaios. Ao se usarem os métodos isolados, o de esclerometria foi o que levou à melhor avaliação da resistência à compressão e a combinação desse método com o de cravação de pinos melhorou a acurácia dessa avaliação. Na impossibilidade de se realizarem ensaios de módulo de elasticidade, o ensaio de velocidade de propagação de ondas ultra-sônicas pode ser uma opção interessante para a avaliação dessa grandeza.

Palavras-chave: curvas de correlação, ensaios não destrutivos, concreto usinado

[a] COPPE, Programa de Engenharia Civil, Universidade Federal do Rio de Janeiro, mauriciodornellas@hotmail.com, Caixa Postal 68506, CEP 21941-972, Rio de Janeiro, Brasil

[b] Escola de Engenharia, Departamento de Engenharia Civil, Universidade Federal Fluminense, lidiashehata@vm.uff.br, COPPE-UFRJ, lidia@coc.ufrj.br,Caixa Postal 68506, CEP 21941-972, Rio de Janeiro, Brasil

[c] COPPE, Programa de Engenharia Civil, Universidade Federal do Rio de Janeiro, ibrahim@coc.ufrj.br, Caixa Postal 68506, CEP 21941-972, Rio de Janeiro, Brasil.

1. Introduction

The compressive strength of concrete is of fundamental importance in structural design, being defined as the compressive strength attained by the material under controlled temperature and humidity conditions, at a certain age.

The verification that the concrete used in the construction of the structure complies with the design requirements is made from compression strength tests, usually at 28 days, on cylindrical or cubic specimens, moulded, cured and loaded to failure according to the technical standards used in each country. However, for different reasons, many times the investigation of the concrete within a structure is required.

The need to evaluate the strength of the material *in situ* at ages below 28 days, for reasons inherent to the construction stages, or at ages after the construction, to verify the need to carry out repairs and/or strengthening, has led to the development or improvement of several tests for the characterization of the concrete.

The extraction of concrete samples from the structure, and its subsequent compressive tests, has the disadvantages of being costly and of the restriction of the places where samples can be cut from, so that the stability of the structure is not impaired. As a result, the cores are usually drilled only from the slabs and in relatively small number, not allowing the full mapping of the strength levels of the concrete in the structure.

The use of non-destructive tests comes then as an alternative, given that the structural element to be evaluated undergoes no damage at all or small ones, easily repairable, that do not compromise its performance, therefore allowing a wider investigation of the concrete within the structure.

These tests, however, have to be carried out according to adequate procedures and should have their results carefully analyzed, given that they are affected by several factors, some of them related to the compression strength of the concrete and others to the type of test. There is a consensus that obtaining reliable results depends on the qualification of the testing personnel and on the use of adequate correlation curves, developed for the type of concrete under study.

Thus, correlation curves to evaluate the compressive strength of ready-mixed concretes used in Rio de Janeiro, using different non-destructive tests, were obtained and are presented here.

A non-linear multiple regression study, which aimed at evaluating the accuracy increase in the compressive strength estimation with the use of combined non-destructive tests methods, is also presented in this work.

The results of the initial tangent modulus of elasticity tests for the same concretes, obtained in a study that was conducted in parallel, also allowed correlating this property with the ultrasonic wave pulse velocity.

2. Evaluation of the compressive strength by non-destructive tests

The estimation of the compressive strength (f_c) using non-destructive tests is made with curves that correlate f_c with the quantities measured in these tests. Obtaining reliable results depends on the use of adequate correlation curves, developed for the type of concrete under study.

According to Malhotra [1], whenever there are changes in the materials involved in the production of the concrete, a new correlation curve should be developed. Considerable errors may be made in the evaluation of f_c if correlation curves provided by the manufacturers of the non-destructive equipment are used, given that they were developed for specific test conditions and materials.

According to ACI 228.1R-03 [2], the use of non-destructive tests in the field should be preceded by the development of correlation curves, from laboratory tests done on standard concrete specimens (cylindrical or cubic) made with the same materials used in the structure's concrete that is under evaluation. Measurements of a particular quantity are carried out on these specimens, using a non-destructive test and, immediately after that, they are submitted to the compressive tests. Finally, the pairs of obtained results are analysed to determine the expressions that best characterize the desired correlation.

In some cases, as in the penetration resistance method, the tests are done on specimens that are different from those that are used in the compressive strength test. In these cases, it is essential that both tests are done on samples of same maturity and compaction conditions.

According to Neville [3], the major hurdle for obtaining adequate correlation curves is that the factors that affect the compressive strength do not always affect the quantities obtained from the non-destructive tests in the same proportion or in the same manner.

3. Experimental programme

In order to propose curves that correlate the compressive strength or the modulus of elasticity with the quantity obtained from the concrete non-destructive tests, the experimental programme covered specimen tests with concrete supplied to construction work by 5 concrete suppliers and produced in the laboratories of 2 concrete supplier groups.

In the first stage it was sought to obtain from each concrete supplier, previously selected based on their market share, two concretes with nominal f_{ck} values equal to at least 25 MPa and different between themselves. However, with only one exception, in the 180-day period (January to June 2004), it was possible to collect only concretes with a nominal f_{ck} of 25 MPa or 30 MPa, minimum values prescribed by NBR 6118 [4] for moderate and high environmental aggressivity.

In the second stage (July to December 2004), aiming to include concretes with more varied strengths and the two typical coarse aggregates of Rio de Janeiro, specimens moulded in the mentioned laboratories, with concretes of a composition similar to that which would normally be adopted by the concrete supplier plants, were tested. In these concretes the variables were the water-cement ratio (0.40, 0.45, 0.50, 0.55 and 0.60) and the petrographic characteristic of the coarse aggregate (crushed granitic gneiss and syenite). The composition of the concretes of this stage is presented by Machado [12].

The following tests were carried out, both in the 1st as in the 2nd stage: compressive strength tests and ultrasonic pulse velocity, rebound hammer and penetration resistance tests. The static modulus of elasticity tests (initial tangent) were done by Nunes [13], using the same concretes of this study, and their results were used to obtain the curve that correlates the modulus of elasticity with the ultrasonic wave pulse velocity.

Table 1 – Summary of the experimental programme carried out

Stage	Concretes	Nominal f_{ck}	Coarse aggregate	w/c
1st	1 to 4	25 MPa	Gneiss, $D_{max.}$=19 mm	Not informed by the producer
	5 to 7	30 MPa	Gneiss, $D_{max.}$=19 mm	
	8	35 MPa	Gneiss, $D_{max.}$=19 mm	
2nd	A1 to A5		Gneiss, $D_{max.}$=19 mm	Varied from 0.40 to 0.60, with increments of 0.05
	B1 to B5		Syenite, $D_{max.}$=19 mm	
	C1 to C5		Gneiss, $D_{max.}$=19 mm	

Tests

Compressive strength
Standard: NBR 5739 (5)
Number of tests: 400
N° of tested CP per age: 4 cylindrical CP
$f_{cm,j} \rightarrow$ mean of $4_{fci,j}$ values

Ultrasonic pulse velocity
Standard: NM 58 (6)
Number of tests: 400 (800 measurements of V)
N° of tested CP per age: 4 cylindrical CP
Equipment:Pundit, transducers:54 kHz and d = 50 mm
Transducers arrangement: direct transmission
$V_{i,j} \rightarrow$ mean of 2 V values
$V_{m,j} \rightarrow$ mean of 4 $V_{i,j}$ values

Rebound hammer
Standard: NM 78 (7)
Number of tests: 400 (3600 measurements of IE)
N° of tested CP per age: 4 cylindrical CP
Equipment: Proceq-Digi Schimdt ND type
Measurements: Equipment in the horizontal position
Load applied to prevent CP movement:
Approximately 15 % of the failure load
$IE_{i,j} \rightarrow$ mean of 9 IE values
$IE_{m,j} \rightarrow$ mean of 4 $IE_{i,j}$ values

Penetration resistance
Number of tests: 95 (380 fired probes)
1 face of prismatic CP tested per age
4 fired probes per face
Equipment: Walsywa gun and probes with 55 mm
length and 6,35 mm diameter
Driver unit: standard driving recommended in (8)
$L_{e,i,j} \rightarrow$ mean of 4 L_e values
$L_{em,j} \rightarrow$ mean of 4 $L_{e,i,j}$ values
$L_{pm,j}$ = probe length (55mm) - $L_{em,j}$

Samples (CP)
400 cylindrical CP
(150 mm x 300 mm) and
44 prismatic CP
(200 mm x 200 mm x 725 mm)

Tests age
1st Stage
3, 7, 14, 28 and 90 days
2nd Stage
3, 7, 14 and 28 days

Cement type
CP III
(equivalent to ASTM type IS)

CP moulding
Rodding
according to NBR 5738 (19)

Curing conditions
Cylindrical CP
For the 3 days tests,
under laboratory conditions
For other ages tests,
moist curing up to 48 h
before the tests
Prismatic CP
Covering with blankets,which were
wetted 3 times per dayand
taken away 48 h before the tests

Range of the obtained values
f_c: 12.9 to 61.2 MPa
V: 3.7 to 4.7 km/s
IE: 22 to 45
L_P: 38.71 to 14.63 mm
E_c: 18 to 35 GPa (13)

Three combined non-destructive methods were studied here, obtaining of the correlation between the ultrasonic pulse velocity, the rebound number and the compressive strength of the concrete (V x IE x f_c), the correlation between the ultrasonic pulse velocity, the probe penetration length and the compressive strength of the concrete (V x Lp x f_c) and the correlation between the rebound number, the probe penetration length and the compressive strength of the concrete (IE x Lp x f_c).

Table 1 summarizes the experimental programme developed. The concretes of the 1st stage were produced by five different concrete suppliers and those of the 2nd stage were produced by two concrete suppliers (concretes A and B by one of them and C by the other). The non-destructive tests carried out are shown in Figure 1.

Compressive strength tests, ultrasonic pulse velocity tests and the rebound hammer tests were done according to the recommendations of the NBR 5739 [5], NM 58 [6], and NM 78 [7], respectively. The Mercosul standards were used as they present, apart from the non-destructive tests recommendations, the procedure for obtaining the correlation curves. Besides the recommendations of these standards, those in the equipment manuals provided by the manufacturers were also followed

The system used in other countries to perform the penetration resistance test is named Windsor probe, while in Brazil the Brazilian Method, developed by Vieira [8], is adopted, in which a gun and Brazilian-made probes are used. As shown in Table 2, the Brazilian Method has gaps in the procedures that have to be adopted during the execution of the penetration resistance tests. Due to that and to the fact that there is no Brazilian Standard for this type of test, this work followed the recommendations of the American Standard ASTM C803 [9] and, for the selection of valid length of exposed probe measurements, the British Standard BS 1881:Part 207 [10]. In spite of all the precautions taken during the execution of the tests, incoherent exposed probe length values (L_e) were found, that is, L_e values in later ages smaller than those obtained in earlier ages, fact also found in the tests carried out by Evangelista [11]. Apart from that, the tests showed coefficients of variation over 5%, limit recommended by ACI 228.1R-03 [2].

Having discarded the possibility that these incoherencies could have occurred due to inadequate procedures during the tests, a decision was made to seek a limit value for the selection of valid L_e values that would be more adequate to the length of the probe used in Brazil. The need to establish this new limit comes from the fact that the length of the probe used in Brazil (55 mm) is smaller than the one used in the USA and in Europe (around 80 mm). Besides that, the limit value for the L_e difference of one probe to the other in the same region recommended by the British Standard [10], 5mm, is stricter than that set by the USA Standard [9], 8.4mm or 11.7mm, as shown in Table 2.

The criterion used in establishing this new limit, described in detail by Machado [12], consisted of considering the average of only 3 L_e values from the 4 obtained, discarding the one that showed the greatest difference in relation to the average value of the 4 obtained. The differences between the L_e value of the excluded probe and the greatest or smallest L_e value of the remaining 3 probes showed that the value recommended by BS 1881:Part 207 [10], 5mm, was more adequate to use in the analysis of the tests undertaken in this work.

4.   Results

4.1   Isolated Methods

In the studies carried out by Evangelista [11], where the coarse aggregate and water volumes were kept constant, on concrete

Figure 1 – Tests carried out

Ultrasonic pulse velocity test

Rebound hammer test

Penetration resistance test

specimens with the same coarse aggregates used in this work, it was found that the factors that affected the V x f_c correlation the most were the density of the coarse aggregate and the type of the cement. According to that same author, these factors were the

	BS 1881:Part 207 1992	ASTM C803 1990	Brazilian Method 1978
Table 2 – Comparison between procedures recommended by BS 1881:Part 207 (10) and ASTM C 803 (9) and by Brazilian Method (8) for the penetration resistance test			
Minimum distance between probes	200 mm	175 mm	No value is mentioned.
Minimum distance ween probes and edges	150 mm	100 mm	No value is mentioned.
Minimum fired probes per region	3, in area not defined	3, in area not defined	5 in a 30 cm x 30 cm area
Test validity	Minimum of 3 valid probes (difference between Le values of the probes should not be over 5 mm)	Minimum of 3 valid probes (difference between L_e values of the probes should not be over 8.4 mm for concretes I and 11.7 mm for concretes II).	No criterion is established for the selection of valid probes.
Results	Mean of at least 3 valid penetrations.	Mean of at least 3 valid penetrations.	Mean of at least 5 penetrations.
Used system	Windsor Probe	Windsor Probe	WALSYWA Gun and probes
Driver unit position	Different power should be used for different concrete strength range, according to equipment manufacturer's Instructions	Low Power (1) Standard Power	Standard Power (2)
Probes	Length: about 80 mm	Probe 1 Length: 79,4 mm Diameter: 7,94 mm 6,35 mm (end) Probe 2 Length: 79,4 mm Diameter: 7,94 mm	Length: 55 mm Diameter: 6,35 mm

L_e – exposed probe length.
Concrete I – concrete with maximum aggregate size equal to 25 mm
Concrete II – concrete with maximum aggregate size equal to 50 mm.
(1) – for concretes with density equal to or greater than 2000 kg/m^3 or f_c less than 17.2 MPa.
(2) – for all concretes, regardless the value of f_c.
Probe 1 – used for concretes with density equal to or greater than 2000 kg/m^3.
Probe 2 – used for concretes with density less than 2000 kg/m^3.

ones that influenced the IE x f_c correlation the most, while the type of cement and the maximum aggregate size were the ones to most affected the Lp x f_c correlation.

These findings served as the basis to decide for the use, in the simple non-linear regression studies aiming at the selection of the curve that best represented the correlation between the quantities measured in the non-destructive tests and f_c, the experimental data obtained in the 1st and in the 2nd stage of this work simultaneously; given that in all of the concretes tested the same type of cement and coarse aggregates with nearly identical density and volume and with the same maximum size were used.

In the absence of a detailed study on the factors that affect the V x E_c relationship, the decision to use the experimental data obtained in the 1st and 2nd stages simultaneously was made by taking into account the work developed by Nunes [13], who studied the same concrete specimens of this study. In it, practically no difference was found between the expressions that relate E_c and f_c obtained for each concrete group tested and that related to all the obtained experimental data.

In this study, for each correlation, the five most commonly proposed curve models in the literature were tested: linear, power, exponential, polynomial (2nd degree) and logarithmic. The criterion to select the curve that best fitted the experimental data was based on the coefficient of determination (r^2) and the residual standard deviation (S_{res}), as well as the statistical parameter (α), equal to (S_{res}) divided by the mean value of f_c or E_c. The power curves were those that best represented the V x f_c and IE x f_c correlations, while the 2nd degree polynomial ones were those that best represented the correlations between Lp and f_c and between V and E_c.

The expressions proposed to correlate the concrete compressive strength with the ultrasonic pulse velocity, with the rebound number and with the probe penetration length, along with the expression proposed to relate the modulus of elasticity with the ultrasonic pulse velocity, are shown in Table 3. Figures 2, 3, 4, and 5 show, respectively, the curves that represent the expressions given in Table 3, along with the 95% prediction intervals, apart from all the obtained experimental data. In order to obtain these expressions, the data that were distant from the mean of a value equal to or greater than three times the standard deviation were discarded (see Figures 4 and 5).

Analysing the results related to the expressions for the evaluation of f_c shown in Table 3, it is found that the IE x f_c relationship is the one that presented the greatest value of r^2 and the smallest value of (α), followed in decreasing order by the Lp x f_c and V x f_c relationships, in line with the sequence found by Yun et al [14] and Samarin and Meynink [15].

According to Popovics [16], the estimation of the concrete compressive strength cannot be obtained with an acceptable accuracy with the use of expressions where the only variable is the value for V. This fact was verified in this work, given that the V x f_c relationship is the one which showed the smallest value of r^2 and the largest value of α amongst all of the studied relationships. According to that author, preliminary studies demonstrated that the inclusion of a new variable (age of the concrete) in the expressions that relate V with f_c provides an improvement in the accuracy of the estimated f_c value.

Comparing the values of r^2 and of α obtained for the V x f_c relationship with those obtained for the V x E_c relationship, one finds that the latter leads to more accurate values of the estimated quantity as it presented a greater value of r^2 and a smaller value of α than the V x f_c relationship. This fact had been anticipated given that the ultrasound pulse velocity is a measure of elastic stiffness and is directly related to the modulus of elasticity [17].

It should be noticed that the values of f_c and E_c, obtained from the expressions shown in Table 3, correspond to the mean values located within the range set by the upper ($f_{c,sup}$ or $E_{c,sup}$) and lower ($f_{c,inf}$ or $E_{c,inf}$) limits of the prediction interval. Since these limits were obtained from 95% prediction intervals, it can be said that there is a 95% chance of the f_c or E_c value to be inside these limits. The expressions for the calculation of these limits are shown in Table 4.

Table 3 – Proposed expressions to correlate f_c with V, f_c with IE, f_c with Lp and E_c with V.

Correlation	Curve	r^2	S_{res}	α*(%)	Expression**
V x f_c	Power	0.640	6.30 MPa	18.6	$f_c = 0.036 \, V^{4.696}$
IE x f_c	Power	0.899	3.45 MPa	10.2	$f_c = 0.026 \, IE^{2.044}$
Lp x f_c	Polynomial	0.778	4.66 MPa	13.6	$f_c = 0.045 \, Lp_2 - 4.043 \, Lp + 107.1$
V x E_c	Polynomial	0.814	1.80 GPa	6.9	$E_c = 7.724 \, V_2 - 48.97 \, V + 94.24$

* α – statistical parameter

$$\alpha = \frac{S_{res}}{f_{cm,obs}} \quad \text{or} \quad \alpha = \frac{S_{res}}{E_{cm,obs}}$$

** f_c in MPa, V in km/s, IE dimensionless, Lp in mm and E_c in GPa.

The expressions of this table and the prediction intervals shown in Figures 2, 3, and 4 confirm the previously mentioned conclusion drawn from the values of r^2 and α: the IE x f_c relationship is the one which presented the smallest uncertainty range for the values of f_c amongst the relationships studied in this work.

When conducting an evaluation of the f_c by means of non-destructive tests or of E_c from the V x E_c relation, one should always bear in mind the purpose of such evaluation. One should verify if the uncertainty range for the values of f_c or E_c inherent to all methods is aligned with the accuracy required by the work to be undertaken.

Table 4 Expressions for the calculation of the superior and inferior limits of isolated methods.

4.2 Combined Methods

In the nonlinear multiple regression studies, aiming at choosing the curves that best represented the V x IE x f_c, V x Lp x f_c, and IE x Lp x f_c correlations, the experimental data obtained in the 1st and 2nd stages were used simultaneously, as justified above.

Tests were done with 10 types of curve [12] for each correlation, with the choice being made for those that showed the greatest coefficient of determination (R^2). The expressions proposed for the 3 combined methods studied here are shown in Table 5.

Aiming at evaluating whether an increase in the accuracy of the estimate of f_c had taken place with the use of the combined meth-

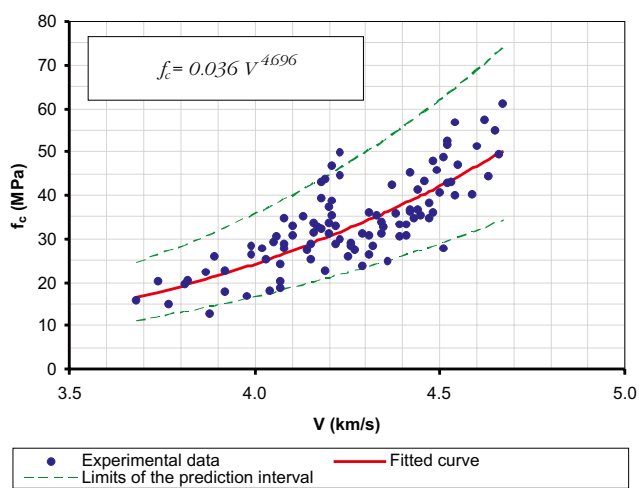**Figure 2 – Curve that correlates f_c with the ultrasonic pulse velocity (V)**

$f_c = 0.036\ V^{4696}$

Figure 3 – Curve that correlates f_c with the rebound number (IE)

$f_c = 0.026\ IE^{2.044}$
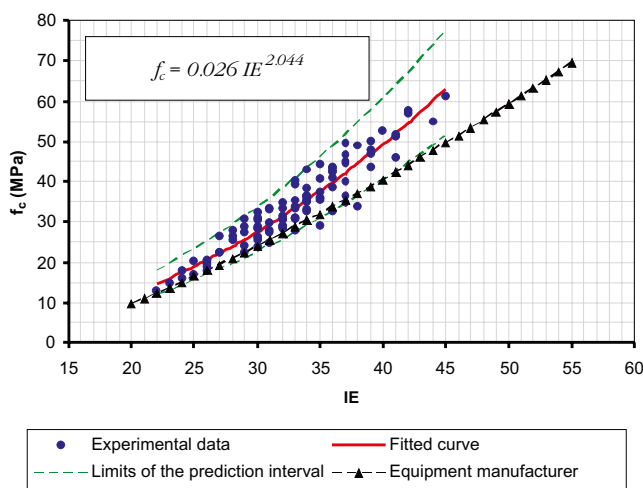
Figure 4 – Curve that correlates f_c with the probe penetration length (Lp)

$f_c = 0.045\ Lp^2 - 4.043\ Lp + 107.1$
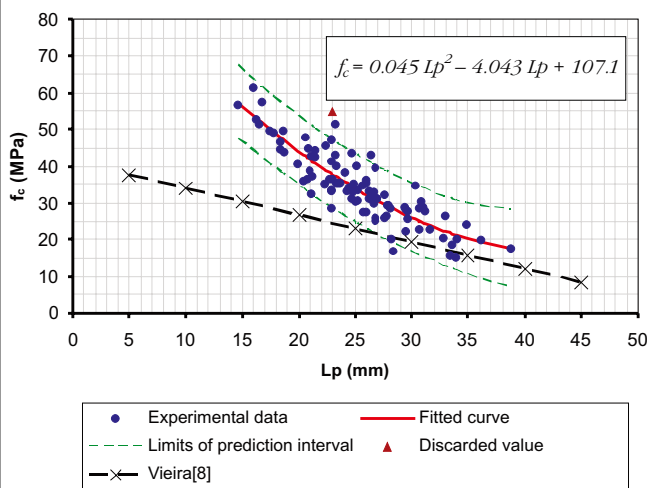
Figure 5 – Curve that correlates E_c with the ultrasonic pulse velocity (V)
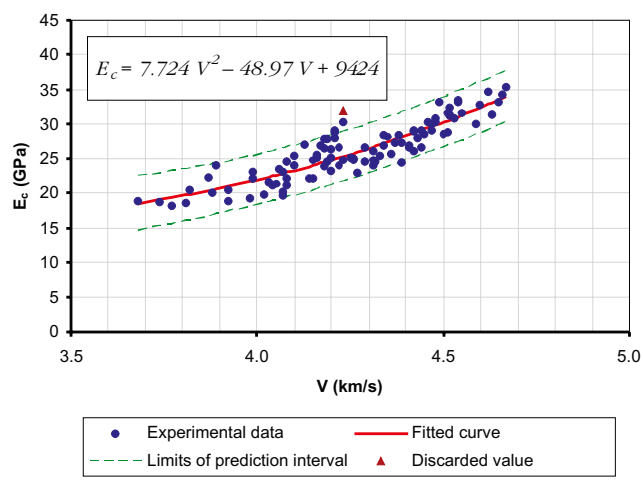
$E_c = 7.724\ V^2 - 48.97\ V + 9424$

Table 4 – Expressions for the calculation of the superior and inferior limits of isolated methods

Correlation	Limits
$V \times f_c$	$f_{c,sup} = 1.47\ f_c$ $f_{c,inf} = 0.68\ f_c$
$IE \times f_c$	$f_{c,sup} = 1.23\ f_c$ $f_{c,inf} = 0.81\ f_c$
$Lp \times f_c$	$f_{c,sup} = f_c + 9.4\ MPa$ $f_{c,inf} = f_c - 9.4\ MPa$
$V \times E_c$	$E_{c,sup} = E_c + 3.6\ GPa$ $E_{c,inf} = E_c - 3.6\ GPa$

f_c – Values calculated from equations of table 3.

Table 5 – Proposed expressions for the combined methods

Correlation	R^2	α (%)	Expression*
$V \times IE \times f_c$	0.999	11.7	$f_c = e^{(0.048\ IE + 0.446\ V)}$
$V \times Lp \times f_c$	0.999	12.5	$f_c = V^{3.613}\ Lp^{-0.539}$
$IE \times Lp \times f_c$	0.999	8.8	$f_c = IE^{1.422}\ Lp^{-0.455}$

* f_c in MPa, V in km/s, IE dimensionless, Lp in mm and E_c in GPa.

In relation to the combined methods, it is found that the analysis of only the values of R^2 does not allow to evaluate which of the 3 tested combinations provides more accurate values of f_c, as they showed the same value of R^2 (0.999). Using criterion (B), however, one can say that the values of f_c estimated by the IE x Lp x f_c relationship are more accurate than those estimated by the other 2 studied combinations, as it led to the smallest values of S_{res} and α.

Using criterion (A) in the evaluation of the increase in accuracy of the estimate of f_c with the combined methods, it is found that the 3 studied combinations showed an accuracy that was considerably higher than those observed in the isolated correlations, which would justify the use of the combinations. The combined methods led to values of R^2 above the values of r^2 found for the V x f_c (increase of 56%), IE x f_c (increase of 11%) and Lp x f_c (increase of 28%) relationships.

When performing this same evaluation with criterion (B), one can see that the estimate of f_c would be more accurate with the use of combined methods V x Lp x f_c and IE x Lp x f_c than with the use of the corresponding isolated methods, as the values of S_{res} and α found for the combined methods were below those found for the isolated methods. However, in opposition to the conclusion that criterion (A) pointed, the increase in accuracy would hardly justify the additional time and cost that the use of these combined methods would bring about. This comes from the fact that the smallest values of the difference in percentage terms between the α value found for a combined method and those which were found for the isolated methods (β) are relatively

ods in comparison with that obtained with the use of an isolated method, Table 6 was prepared.

In the literature consulted, two criteria were found to evaluate the accuracy of a particular relationship in comparison with that which was obtained by the others. These criteria were named in this work as (A) and (B). In criterion (A), adopted by the vast majority of the authors, this evaluation is made by taking into account only the value of the coefficient of determination, that is, the larger its value, the greater the accuracy. As regards criterion (B), used by Samarin and Meynink [15] and Popovics [16], this evaluation is made with the analysis, apart from the coefficient of determination, of the values of S_{res} and α. According to this criterion, the most accurate relationship is that which presents the smallest values of S_{res} and α.

Analysing only the correlations obtained with the use of one single non-destructive test, it is found that the two mentioned criteria lead to the same conclusion: the values of f_c estimated by the IE x f_c relation are more accurate than those estimated by the V x f_c and Lp x f_c relations, given that for that relation the greatest value of r^2 and the smallest values of S_{res} and α were found.

Table 6 – Comparison between the values of r^2 or R^2, S_{res}, α and β found for the studied correlations

Correlation	r^2 or R_2	S_{res} (MPa)	α (%)	β (%)
$V \times f_c$	0.640	6.30	18.6	6.9
$IE \times f_c$	0.899	3.45 *	10.2 *	-1.5 ***
$V \times IE \times f_c$	0.999	3.96	11.7	
$V \times f_c$	0.640	6.30	18.6	6.1
$Lp \times f_c$	0.778	4.66	13.6	1.1**
$V \times Lp \times f_c$	0.999	4.32 *	12.5 *	
$IE \times f_c$	0.899	3.45	10.2	1.4 **
$Lp \times f_c$	0.778	4.66	13.6	4.8
$IE \times Lp \times f_c$	0.999	3.04 *	8.8 *	

β – difference, in percentage, between the value of α found for a combined method and those found for the respective isolated methods.
* Smallest values of S_{res} and α.
** Smallest values of β.
*** No accuracy increase with the use of the combined method

small, not going beyond 2%, as shown in Table 6. In this same table, one can see that the use of the V x IE x f_c combined method is not viable, since it led to values of S_{res} and α above those found for the IE x f_c correlation.

In the attempt to eliminate doubts about the viability of using the combined methods, as the two criteria led to contradictory conclusions, tables with the errors of the estimate of f_c related to each one of the 6 proposed expressions were produced by Machado [12]. These errors were calculated by taking into account the difference between the values of f_c obtained from a particular expression and those obtained from the standard compressive strength tests. A summary of the analysis of these results is shown in Table 7.

Based on the results shown in tables 6 and 7, one can say that:

a) As far as the isolated methods is concerned, criteria (A) and (B) showed to be adequate to point, amongst various relations, that where the values of f_c are estimated with more accuracy, as the IE x f_c relation, pointed by the 2 criteria as being the most accurate, was the one that presented the smallest relative errors, 7.9% against 15.4% of the V x f_c relation, and 7.6% against 12% of the Lp x f_c relation.

b) Criterion (B), in opposition to criterion (A), showed adequacy to point, amongst various combined methods, that where the values of f_c are estimated with greatest accuracy. The IE x Lp x f_c relationship, pointed by criterion (B) as being the most accurate, was the one that presented the smallest relative errors, 7.1% against 8.9% and 10.9% of the V x IE x f_c and V x Lp x f_c relationships, respectively.

Table 7 – Summary of the analysis of errors in f_c estimation by a certain relationship

Correlation	Mean error (%)	X (%)
V x f_c	15.4	6.5
IE x f_c	7.9 *	-1.0 ***
V x IE x f_c	8.9	
V x f_c	13.9	3.0
Lp x f_c	12.0	1.1 **
V x Lp x f_c	10.9 *	
IE x f_c	7.6	0.5 **
Lp x f_c	12.0	4.9
IE x Lp x f_c	7.1 *	

X – Difference, in percentage, between the relative error found for a combined method and those found for the respective isolated methods.
* Smallest mean error value.
** Smallest values of X.
*** No accuracy increase with the use of the combined method.

Table 8 – Expressions for calculating the superior and inferior limits of the combined methods

Correlation	Limits
V x IE x f_c	$f_{c.sup} = 1.26\ f_c$ $f_{c.inf} = 0.79\ f_c$
V x Lp x f_c	$f_{c.sup} = 1.31\ f_c$ $f_{c.inf} = 0.76\ f_c$
IE x Lp x f_c	$f_{c.sup} = 1.21\ f_c$ $f_{c.inf} = 0.83\ f_c$

f_c – Values calculated from equations in table 5.

c) The great difference between the values of R^2 found for the combined methods and those of r^2 found for the respective isolated methods, according to criterion (A), indicates a considerable increase in accuracy for the estimate of f_c with the combined methods, which would justify their use. This fact, however, was not confirmed by the results of the percentage differences between the relative error found for the combined method and those which were found for the respective isolated methods, X, seen in Table 7, which shows the inefficiency of this criterion for this type of evaluation.

d) Criterion (B), in its turn, proved to be adequate for evaluating the viability of the combined methods. In the comparisons made in Table 7 between a particular combined method and the respective isolated methods, the values for X point that, in general, the combined methods showed a discrete increase in accuracy for the estimate of f_c. This was not found only in the comparison between the V x IE x f_c and IE x f_c relations.

The correspondence between these conclusions and those which were obtained with that criterion attests its validity for this type of evaluation.

It should be noticed that the values of f_c, obtained from the expressions in Table 5, correspond to mean values within the range set by the upper and lower limits of the prediction interval. The expressions for the calculation of these limits are shown in Table 8.

From the expressions in this table, one can say that the values of f_c estimated with the IE x Lp x f_c relation showed an accuracy greater than the ones estimated with the relations of the other 2 studied combinations, given that it had the smallest 95% prediction interval for the values of f_c. This same conclusion had already been arrived at from the analysis of the values of S_{res} and α.

A comparison between the 95% prediction intervals of the relationships studied in this research is shown in Table 9.

From the analysis of the values of this table, one can see that:

a) The V x IE x f_c relation presented a prediction interval smaller than that found in the V x f_c relation albeit greater than that found in the IE x f_c relation, which does not justify its use.

b) The V x Lp x f_c relation presented a prediction interval smaller than those found in the V x f_c and Lp x f_c relations. Despite

Table 9 – Comparison between the 95% prediction intervals of the studied relationships

Correlation	95% prediction interval*
V x f_c	0.79 f_c
IE x f_c	0.42 f_c
V x IE x f_c	0.47 f_c
V x f_c	0.79 f_c
Lp x f_c	0.60 f_c**
V x Lp x f_c	0.55 f_c
IE x f_c	0.42 f_c
Lp x f_c	0.60 f_c**
IE x Lp x f_c	0.38 f_c

* Difference between the values of $f_{c,sup}$ and $f_{c,inf}$.
** Obtained from the mean of the differences between the superior and inferior limits of the 95% prediction interval and the predicted values.

that, its use may not be economically viable due, especially, to the small difference between its prediction interval and that of the Lp x f_c relation.

c) The IE x Lp x f_c relation presented a prediction interval smaller than those found in the IE x f_c and Lp x f_c relations but may also not be economically viable due to the small difference between its prediction interval and that of the IE x f_c relation.

Curves that represent the IE x Lp x f_c correlation, combined method that showed the best results, are shown in Figure 6.

5. Conclusions

On the basis of the analysis of the obtained results, the following remarks can be made:

a) As far as the isolated non-destructive methods is concerned, it was found that the correlation between the rebound number and the compressive strength was that which presented the best results, followed in decreasing order by the Lp x f_c and V x f_c correlations.

The worst results showed by the V x f_c relationship could be explained, according to Popovics [16], by the non-existence of a theoretical relation between the compressive strength and the ultrasonic pulse velocity, not even for homogeneous materials and with elastic linear behaviour. This explanation, however, does not seem sufficient to justify that fact, for the simple reason that there is no theoretical relation between the compressive strength and the other quantities (IE and Lp). Analyses made by Machado [12] show that the ultrasonic pulse method is more affected by changes in the concrete

composition than the other methods, and this explanation may be more adequate.

In spite of presenting the worst results in this study, the estimate of f_c using the ultrasound pulse method should not be discarded, especially for an evaluation at later ages. In these ages, results obtained using the rebound hammer and the penetration resistance methods are affected by carbonation, and may not represent the concrete located within the element. The influence of carbonation is not as significant in the results obtained by the ultrasound wave propagation method, as the thickness of the surface layer is relatively small in comparison with the total path length of the ultrasound wave (case of direct transmission). One should always have in mind that, for evaluating the concrete compressive strength by means of non-destructive tests, regardless the method chosen, the greater the knowledge about the composition of the concrete under investigation, thus implying the use of more appropriate curves, the greater will be the accuracy of the obtained results.

b) In relation to the combined non-destructive methods, it was found that the correlation between the rebound number, the probe penetration length and the compressive strength was the one which presented the best results. This is in accordance to the assertion in RILEM NDT4 [18] that the combination of 2 or more methods is advantageous when the methods in question provide estimates of the compressive strength with similar accuracy levels. The IE x Lp x f_c correlation was obtained from the combination of the 2 isolated methods (IE x f_c and Lp x f_c) that individually showed the best results. Despite the fact that the V x Lp x f_c and IE x Lp x f_c correlations led to an increase in accuracy in the obtained results in comparison to those obtained in the respective isolated methods, this increase may not be enough to justify the time and cost increases produced by the use of the two methods instead of only one.

c) The observed differences between the correlation curves

Figure 6 – Curves that correlate f_c with the rebound number (IE) and the probe penetration length (Lp)

$$f_c = 0.036\ V^{4696}$$
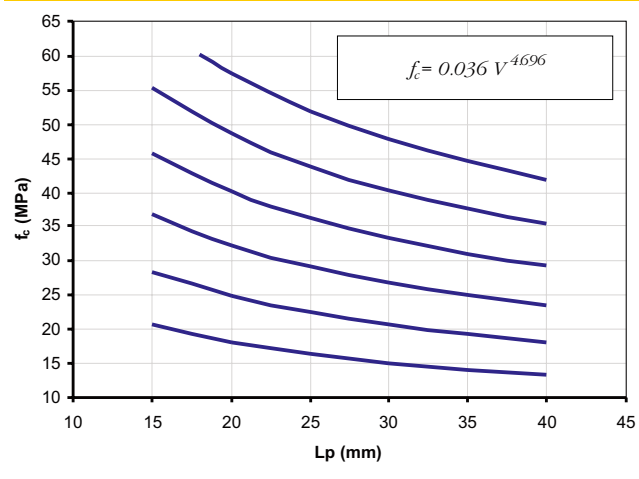
proposed in this and in other works [12] highlight the need to obtain the largest possible number of information about the composition of the concrete under investigation, which will allow the choice of more adequate curves and results that are closer to the real ones. It should be pointed out that the use of these curves should be preceded by verification, made with the extraction of cores, to evaluate their validity. Figures 3 and 4 show that the curves indicated by the manufacturer of the used hammer, and by Vieira [8], do not generally lead to an adequate evaluation of f_c in the case of the concrete specimens analyzed.

d) As regards the statistical procedure adopted, the use of the determination coefficient was proved to be adequate both for the choice of the curve that best represented the correlation studied as for the evaluation, amongst various isolated methods, that one which produced the best results. However, its use does not allow the correct evaluation of the use of combined methods. It is recommended, for the evaluation of the method isolated or combined that provides the best results for a particular data set, that the parameters S_{res} and α are used, apart from the determination coefficient.

e) The estimate of the concrete static modulus of elasticity value by means of the ultrasonic pulse velocity presented rather satisfactory results as a consequence of the direct relationship between these two quantities.

There is in Brazil a vast field to be explored in relation to the improvement of non-destructive tests for obtaining more reliable results: in the training of qualified personnel; in the modification of adopted procedures; in the inclusion of new variables (as age of the concrete) in the expressions that relate the quantities obtained in the non-destructive tests with the concrete compressive strength.

In relation to the penetration resistance method, a broad study is suggested to seek its adaptation to the Brazilian reality, investigating especially the following parameters: minimum number of probes to be fired in a certain region, minimum distance between them, maximum difference between the values of their exposed length, and the ideal driver unit position (power type) as a function of the strength of the concrete under analysis.

6.   Acknowledgements

7.   References

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