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Utilization of the ultrasonic method to evaluate the properties of high performance concrete

Utilização do método ultra-sônico para avaliação da performance do concreto de alto desempenho

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Abstract

The present paper deals with the utilization of the ultrasonic method to evaluate the properties of high performance concrete. The compressive strength and the elasticity module of the concrete are evaluated. A comparative study was performed with the results obtained in the test with the ultrasonic method and in the test with strain gages.
The latter were then compared with the elastic module estimated in accordance with the CEB 90 [1] and the NBR 6118 [2] equations. The study shows that test with the ultrasonic method is sensible to variations in the mechanical properties of concrete. Furthermore, the comparative study showed that the elasticity module of concrete may be estimated indirectly by the ultrasonic pulse velocity.

Keywords: ultrasonic pulse velocity; high performance concrete; mechanical properties; non-destructive tests.

Resumo

O presente trabalho trata da utilização do método ultra-sônico para avaliar a desempenho do concreto de alto desempenho. As propriedades mecânicas avaliadas foram a resistência à compressão e o módulo de elasticidade. Com respeito ao módulo, foi feito um estudo comparativo entre os resultados obtidos com o aparelho de ultra-som e com extensômetros colados. Os resultados obtidos em ambos os ensaios foram também contrastados com os valores previstos de acordo com o CEB 90 [1] e a NBR 6118 [2].
Através desse estudo se verificou que as leituras realizadas com o método ultra-sônico são sensíveis às variações das propriedades mecânicas. Por outro lado, a análise comparativa do módulo de elasticidade mostrou que é possível estimar o seu valor por meio dos resultados obtidos com o aparelho de ultra-som.

Palavras-chave: ultra-som; concreto de alto desempenho; propriedades mecânicas; ensaios não destrutivos.

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1. Introduction

The concern about the environment is present nowadays in many productive sectors and, especially, in the construction industry that is one of the biggest responsible for the environmental impact generated. In this context, the natural sand extraction becomes an important matter since it causes a negative impact to the riverine forest and provokes the river siltation.
Each day the natural sand becomes rarer with deposits located further apart from urban centers causing the increase of transportation costs. The crushed sand is one of the alternatives to be used as fine aggregate. Despite this fact, little is known about the behavior of high performance concrete (HPC) produced with crushed sand. This paper intends to contribute to this area.
The HPC differs from the conventional concrete because it shows a smaller water-cement, possible due to the addition of superplasticizers that guarantee the consistence and the workability of the concrete. However, a systematic control of the properties of concrete with time is required, especially in elements exposed to aggressive environments.
The cores extraction in structures is an inconvenient and expensive procedure, in some cases, very difficult to perform. In order to avoid these problems non-destructive tests may be used.
Given the necessity to assess the properties of the HPC and the advantages of performing non-destructive testing, it becomes important to evaluate the applicability of the ultrasonic method for the estimation of the mechanical properties of concrete.
The objective of this paper is to evaluate the accuracy of the ultrasonic method and to establish a mathematical correlation between the ultrasonic pulse velocity and the compressive strength in HPC. To do so, cylindrical specimens were produced and then tested with the ultra-sonic method and for the compressive strength.
The air content, the density, the water absorption and the voids were considered as independent variables. Besides, comparative analysis of elasticity module obtained through equations of pulse velocity equipment, CEB 90 [1] and NBR 6118[2] were performed.

1.1 High performance concrete

According to Metha and Aïtcin [3], the HPC is characterized by a high workability, durability and strength. Such characteristics contribute to an increase in the life of structures and a decrease in the cross sections of beams and columns.
Another definition of HPC was proposed by the U.S Federal Highway Administration [4] after conduction several tests in bridges. The results showed that the assumption that "more resistant concrete are more durable" was not true in this case since concrete mixes with higher initial strength were more likely to present cracks. Such observation motivated a new definition of HPC as a type of concrete projected to be durable and, if necessary, more resistant than the conventional concrete."
According to Metha and Monteiro [4] this definition is practical and useful since it demonstrates that the strength is not a synonym of durability and stresses that the "high performance" should be linked to high durability.
The HPC differs from the conventional concrete because it shows a reduced water-cement ratio and, consequently, a little or almost no permeability. The reduced permeability is paramount to achieve high durability in structures exposed to aggressive environments (Metha and Monteiro [4]; Aïtcin [5]).
According to Aïtcin [5] the HPC is seen as a new type of concrete and its applications are increasing in volume and in diversity. The same author still adds:
"Any concrete structure facing difficult environmental conditions should be cast with high performance concrete in order to increase the life of the structure."
Aïtcin [5] concludes that the increase in the use of HPC and its intelligent monitoring will refine the design methods and raise the life of structures. Thus, what was gained in performance will be lost in simplicity of construction since the production and casting technique would have to evolve from a low technological level to a high technological level.
Mineral additions and chemical additives (such as the superplasticizers) are included in the HPC composition superplasticizer.
The quality control and the properties verification throughout the life of the structure become essential to the construction of durable structures, especially in aggressive environments.
Given the constant control required, a question about how to assess a structure without the inconvenient and difficult core extraction arises.
Nowadays there are several non-destructive methods and techniques to evaluate the characteristics of concrete "in situ". Among these methods is the ultra-sonic test.

1.2 Non-destructive tests

The ultra-sonic pulse velocity equipment performs a non-destructive test, thus avoiding damages to the structure being tested. The first study about the ultra-sonic waves was conducted in the mid 40's in the United States of America. Nowadays, the ultra-sonic test is one of the most used non-destructive tests due to its flexibility during the execution and the low investment required.
The testing procedure with the ultra-sonic pulse velocity equipment is relatively simple, being defined in the NBR NM 58 [6] standard. The testing allows us to evaluate the mechanical properties, elastic properties, composition and damages in materials such as concrete and wood.
The ultra-sonic pulse velocity equipment is composed by a source, in which two transducers are connected. The first transforms electrical impulses into acoustic waves with a frequency above the audible limit that is transmitted to the material analyzed. The second transducer receives these signals, converting them again into electrical impulses. The division between the transit distance and the transit time gives the velocity of the sound wave in the material. In this context, materials with internal discontinuities should present slower velocities than intact materials.
It is important to highlight that almost all existing bibliography about the ultra-sonic technique is related to the estimation of the elasticity module in conventional concretes.
In the present paper, the ultra-sonic pulse velocity equipment used was a PUNDIT. The interface material that serves as a bridge between the specimens tested and the transducer was Vaseline. The measurements were performed in 24 concrete mixes.

1.3 Elasticity module

The elasticity module is a mechanical property that offers a measure of the stiffness of the material. It is obtained from the ratio between the tension applied and the strain. This property is related

Table 1 – Physical characteristics of the CPV-ARI cement

Tests	CP V-ARI
Beggining of setting	3h and1 min.
End of setting	4h and 11 min.
Normal consistence	28.49% of water
Density	3.14 kg/dm³
Sieve fineness 200	------
Sieve fineness 325	1.37%
Specific surface	4430 cm²/g

to the natural vibration frequency of the structures. In other words, a material with low elasticity module has a lower vibration frequency than a material with bigger elasticity module, assuming both of them have the same specific weight. (Aguilar, M.T.P., et al [7]).
According to Metha and Monteiro [4], the concrete is a heterogeneous material with an elastic behavior depending of the characteristics of the transition zone and of the volumetric fraction, the density and the elasticity module of each component. According to ACI 318:05 [8], the concrete elasticity module depends sensibly on the aggregate module. Consequently, the concrete with basaltic aggregate has a higher elasticity module than those of concretes made with quartzitic or calcareous aggregates.
Although the aggregate and the paste mechanical behavior could be considered linear-elastic, the same does not happen with the concrete. The stress-strain relation in the case of concrete can be considered approximately linear for stresses that do not exceed 30% of its compressive strength and 70% of its traction strength. For higher stress values, the deformation is not proportional to the applied stress and strain is not totally reversible after unloading the concrete. Even for low stresses, the deformation may increase if the load application is slower or if the load is sustained for a long period.
Metha and Monteiro [4] report that in concrete the direct relation between strength and elasticity module occurs because both properties are affected by the porosity of the materials, although with slightly different intensities. Therefore, all factors that influence the porosity of the components of concrete are important.
According to the same authors, to determine the stresses due to environmental effects and to calculate the design stress, it is necessary to make an estimation of the elasticity module. It is important to point out that the smaller the elasticity module, the smaller the tension stresses induced by certain shrinkage of the material. Hence, the relation between stress and strain becomes really important for the project of concrete structures and for their monitoring through time.

2. Materials

In order to achieve the objective proposed in this paper, twenty-four distinct types of concrete were produced with four granular skeleton, four paste percentage and two water-cement ratios. Normal weight concrete and light weight concrete were tested with the purpose of covering materials with a wide range of characteristics.
The use of such a large variety of concretes aimed to guarantee a broad study about the use of the ultra-sonic method to estimate indirectly the properties of HPC, more specifically the compressive strength.
The component materials used to produce the concretes were CP V-ARI, natural quartz sand, crushed basaltic sand , basaltic gravel type zero (9.5mm), basaltic gravel type one (19mm) , superplasticizer and silica fume.

2.1 Cement

The performance of the cement in terms of rheology and consistence becomes a critical parameter as the compressive strength required increases. Furthermore, different types and cement brands may have different performances when it comes to HPC.
Some types of cement may present a good performance in terms of compressive strength but a bad rheologic behaviour whereas others may show good rheologic behavior but a poor performance in terms of compressive strength. Therefore, it is necessary to select the correct type of cement in order to produce a HPC with the properties desired.
The CP V-ARI cement was used in all concretes due to its high initial strength given by a higher C_3A content. The characteristics of the cement used in the concrete mixes are shown in table 1.

2.2 Mineral addition

The silica fume is a by-product from the production process of silicon and ferrosilicon alloys. The silicon and its alloys are produced in electric arc furnaces where the quartz is reduced in the presence of coal. As the gases escape to the upper part of the furnace, they cool, condense and oxide in the form of extremely fine silica particles (Aïtcin [9]).
One of the positive consequences of silica fume addition is known as filler effect, which is related to the capacity of the small particles of silica fume to fill the voids among bigger cement particles. This filler effect is also responsible for an increase on the fluidity of concretes with very low water-cement ratios. On the other hand, the silica fume promotes a positive chemical effect leading to the formation of portlandite crystals (Groves [11]).
The physical characteristics of the silica fume used in the present experimental program are shown in table 2. Since the strength gains are significant when the dosage of silica fume increases from

Table 2 – Physical characteristics of silica fume

Tests	Silica
Aparent density	550 kg/m³
Density	2220 kg/m³
Specific surface	20.000 m²/kg
Format of particle	Spheric
Diameter of particle	0,2 μm

Table 3 – Superplasticizer characteristics

Physical characteristics	Superplasticizer
Density (kg/m³)	1.06 ± 0.02
Solids (%)	30.07

5% to 10% by mass of cement (Aïtcin [5]), a content equal to 10% was fixed for all concretes.

2.3 Chemical additives

The water reducers represent an evolutionary mark in the achievement of concrete with higher strength. The appearance of HPC is connected to the new generation of chemical additive that allow a further reduction in the water-cement ratio. This generally leads to a decrease in the number and the dimension of concrete voids, which elevates the durability and the strength of the concrete.
In this paper, a plicarboxilate ether based superplasticizer with the characteristics shown in table 3 was used.
The percentage of superplasticizer used in all concretes was fixed relatively to the cement mass. Furthermore, this percentage is calculated considering the solid material present in each type of superplasticizer used. The dosage of superplasticizer was fixed considering the saturation point, as proposed by Toralles Carbonari (Toralles-Carbonari et al, 2003[4]).

2.4 Fine aggregate

The fine aggregate used for the production of HPC should present a coarser grading represented by a fineness module close to 3,0 (De Larrard [15]). The use of such sands in HPC is supported by the fact that this type of concrete is already rich in fine particles due to the high content of content and additions. Therefore, it is not necessary to use finer sands to guarantee the workability and segregation resistance of the concrete mix. Moreover, the use of a coarser sand contributes to a small decrease in the quantity of water needed to obtain the workability required (Aïtcin [5]).
The fine aggregate used in the experimental program is a natural quartz sand of the region of Nova Londrina, Paraná, Brazil with the characteristics presented in table 4.

Table 4 – Natural fine aggregate

Tests		Sand
Particle size	D_{max} (mm)	2.4
	Fineness module	2.11
Density (kg/dm³)		2.66
Apparent density (kg/dm³)		1.657
Powdery material (%)		0.67
Absorption (%)		1.35

2.5 Coarse aggregate

The HPC strength is usually limited by the mechanical properties of the coarse aggregate. In this sense, it is preferable to use coarse aggregates with strength higher than that of the paste. However, the strength difference should not be high enough to generate stress concentration and cracks in the transition zone.
Another measure to avoid stress concentrations is the reduction of the maximum dimension of the coarse aggregate, which should be below 19,0 mm and preferably between 9,5 mm and 12,5 mm (Toralles-Carbonari [16], Almeida [13], ACI COMMITTEE 363 [17]). It is also recommended to use coarse aggregates with a rectangular shape and a rough surface in order to improve the adherence between the paste and the aggregate.
In the present study, two grading fraction of basaltic coarse aggregates collected in the Parana River were used: a gravel zero with maximum diameter of 9.5 mm and gravel one with a maximum diameter of 19.0 mm. The main characteristics of these aggregates are shown in table 5.

Table 5 – Coarse aggregate

Tests		Crushed Sand	Gravel 0	Gravel 1
Particle Size	D_{max} (mm)	4.8	9.5	19.0
	Fineness module	3.2	5.68	5.84
Density (kg/dm³)		2.92	2.917	2.93
Apparent density (kg/dm³)		1.787	1.535	1.614
Powdery material (%)		18.91	3.66	1.75
Absorption (%)		1.44	0.55	1.02

Table 6 – Granular skeleton

Skeleton	Composition by mass	Bulk Density (kg/dm³)	Void content (%)
A	40% AN + 24% B0 + 36% B1	2.089	25.74
B	16% AN + 60% AB + 24% B0	2.07	27.97
C	36% AN + 10% AB + 22% B0 + 32% B1	2.11	25.26

AN = Natural sand; AB = Crushed Sand; B0 = Gravel 0; B1 = Gravel 1

3. Method

First, the optimum concrete mixes were defined. Then, the different types of concrete were produced and tested in the fresh state and in the hardened state.

3.1 Definition of the optimum Concrete mixes

A study about the dosage was performed in accordance with the methodology proposed by Toralles-Carbonari [16]. This methodology considers the evaluation of the three phases that compose the concrete: paste, granular skeleton and paste-skeleton combination. In total, 24 concrete mixes were proposed with four distinct granular skeletons, four percentages of paste and two water-cement ratios. The variation of all these parameters aimed at evaluating the applicability of the ultrasonic method for the estimation of compressive strength and elasticity module.

The terminology used to refer to each type of concrete according to its dosage characteristics consists of three independent terms [Table 6]. The first term refers to the granular skeleton, the second, to the percentage of paste to fill the void of the granular skeleton and the third, to the water-cement ratio used. For example, A; 15; 0.30 refers to a concrete composed by the granular skeleton A [Table 6], with the paste exceeding the total void of the granular skeleton by 15% and a water-cement ratio of 0.30. The concrete mixes referred by the letter D correspond to lightweight HPC produced with addition of foam.

3.2 Tests in the fresh state

The following tests were performed in order to check the properties of concrete in the fresh state: density (NBR 9978 [22]), consistence through the Abrams cone (NBR 7223 [18]) and air entrainment (NBR 11686 [23]).

3.3 Tests in the hardened state

The properties in the hardened state were evaluated through the following tests: compressive strength according to NBR 5739 [19]; elasticity module with strain gages; ultra-sonic pulse velocity according to NBR 8802[21] and absorption by immersion according with NBR 9778 [20].

It is important to remark that the elasticity module was also indirectly estimated with the equations of the ultra-sonic equipment

Table 7 – Tests and theoretical estimation of different concretes

Concrete	Density (kg/dm³)	Ultra-sonic pulse velocity (m/s)	Compressive strength (MPa)	Elasticity module (GPa)			
				Strain gages	Equations		
					Ultra-sonic equipment	NBR 6118	CEB 90
A; 5; 0.25	2.634	5120.98	90.63	46.32	49.73	53.31	44.83
B; 10; 0.25	2.607	4892.97	87.93	41.19	44.94	52.51	44.38
C; 10; 0.25	2.639	5095.68	82.44	44.07	49.34	50.85	43.43
C; 10; 0.30	2.641	5199.36	86.43	46.56	51.4	52.06	44.12
D; 8; 0.30	2.466	4676.65	70.91	30.9	38.83	47.16	41.31
D[1]; 8; 0.30	1.957	3762.95	24.83	16.9	19.95	27.9	29.11

D = lightweight HPC; D[1] = Light Concrete produced with additive.

(1), according to NBR 6118[2] and to CEB 90 [1] (3). The high cost of the strain gages restricted the number of concrete specimens tested. Table 7 shows the results obtained by the theoretical estimations and by the tests with strain gages.

$$E_c = \frac{V^2 \cdot \delta \cdot (1+\upsilon) \cdot (1-2\upsilon)}{(1-\upsilon)} \times 10^{-3} \quad (1)$$

$$E_c = 5600\sqrt{f_{ck}} \quad (2)$$

$$E_c = 2{,}15 \times 10^4 \sqrt[3]{f_{c28}/10} \quad (3)$$

Where:
E_c = Elasticity module of concrete in MPa;
V = Ultra-sonic pulse velocity in m/s;
δ = Density of concrete (density) in kg/dm³;
υ = Poisson coefficient estimated in 0.20 for the concrete tested;
f_{ck} = Compressive characteristic strength in MPa, $f_{ck} = f_{c28}$;
f_{c28} = Average compressive strength at 28 days in MPa;
The compressive strength determined according to NBR 5739 [19] are shown in table 8. The same table presents the results of

Table 8 – Tests performed in fresh and hardened states

Concrete	Pulse velocity (m/s)	Air entrainment (%)	Total absorption (%)	Void content (%)	Density (kg/dm³)	Compressive strength (MPa)
A; 0; 0.25	5069.72	5.8	1.081	2.76	2.625	69.01
A; 5; 0.25	5120.98	1.6	1.59	4.021	2.634	90.63
A; 10; 0.25	5076.14	2	1.584	4.01	2.637	67.2
A; 15; 0.25	5003.46	0.5	2.219	5.521	2.635	69.36
A; 0; 0.30	5154.64	6	1.443	3.393	2.604	70.03
A; 5; 0.30	5159.17	1	1.569	3.389	2.648	84.27
A; 10; 0.30	5102.06	2	1.784	4.529	2.66	73.86
A; 15; 0.30	5073.17	3.5	2.429	6.041	2.648	70.07
B; 5; 0.25	4747.63	4.6	3.838	9.245	2.66	42.22
B; 10; 0.25	4892.97	2.8	1.659	4.147	2.607	87.93
B; 15; 0.25	4898.96	1.8	1.667	4.147	2.596	94.51
B; 0; 0.30	4773.32	2.7	2.802	6.938	2.661	57.58
B; 5; 0.30	4848.,49	3.6	1.863	4.656	2.621	83.12
B; 10; 0.30	4878.99	1.5	2.831	6.954	2.64	95.06
B; 15; 0.30	4765.11	1.6	2.888	7.131	2.658	92.87
C; 5; 0.25	4971.03	5.4	2.128	5.312	2.642	65.28
C; 10; 0.25	5095.68	2.6	1.462	3.716	2.639	82.44
C; 10; 0.30	5199.36	2.3	2.221	5.542	2.641	86.43
C; 15; 0.30	5047.02	1.3	2.103	5.262	2.643	90.6
D; 8; 0.30	4676.65	3.9	1.88	4.38	2.466	70.91
D[1]; 8; 0.30	3762.95	19	2.11	4.11	1.957	24.83
D[2]; 8; 0.30	3373.41	22	2,5	4.28	1.787	14.51
D[3]; 8; 0.30	3687.99	20	2.1	3.82	1.895	18.82
D[4]; 8; 0.30	4012.76	15	1.93	3.84	2.056	27.52

Figure 1 – Comparison of theoretical estimation and estimation of the elasticity module

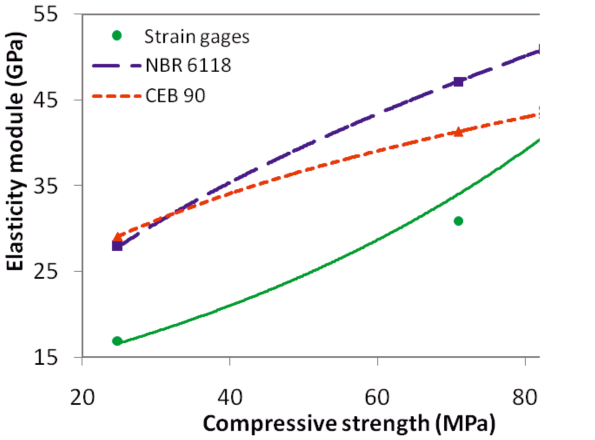
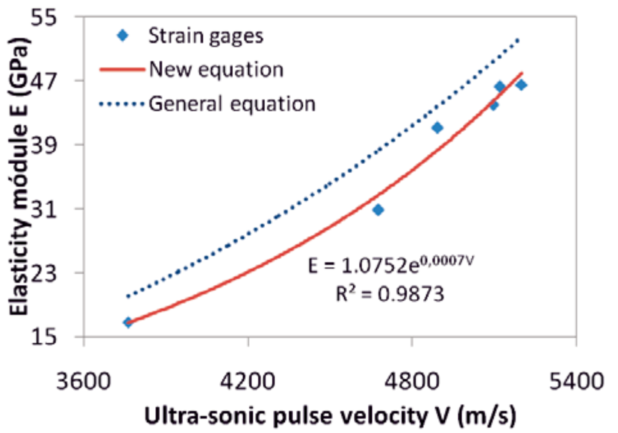


Figure 2 – Correlation between the elasticity module and pulse velocity



the ultra-sonic pulse velocity tests, air entrainment, absorption and density.

4. Analysis of the results

4.1 Evaluation of the elasticity module

The comparison of the elasticity module obtained through the equations of CEB [1] and of NBR 6118[2] indicates that the former fits better the measurements taken in the tests with strain gages. This is especially noticeable for the concrete with compressive strengths higher than 50 MPa (see figure 1).
Nevertheless, both equations presented a poor fit with the experimental results for concretes with lower compressive strength strength, that is, the lightweight HPC. Such behaviour is justified due to the spongy microstructure of these concretes.
It is important to point out the significant imprecision that occurred because of the use of the already mentioned standard equations for the estimation of the elasticity module in high performance concretes. On the other hand, in spite of showing a compressive strength comparable to that of conventional concretes, the special microstructure of the lightweight HPC characterized by a smaller density prevents the indirect estimation of the elasticity module through the equations of the CEB [1] and of the NBR 6118[2].
On the contrary, it was possible to establish a good correlation between the elasticity module measured with strain gages and the estimated with the ultra-sonic pulse velocity as shown in figure 2. Despite the different characteristics of the concrete tested, the level of correlation obtained was high. The same figure also shows the elasticity module obtained by using the ultra-sonic pulse velocity and the general equation suggested by the ultra-sonic equipment manufacturer. It is verified that this equation presents an almost constant difference of 5 GPa with the new equation proposed in the present study, which yields a much better approximation of the experimental results..

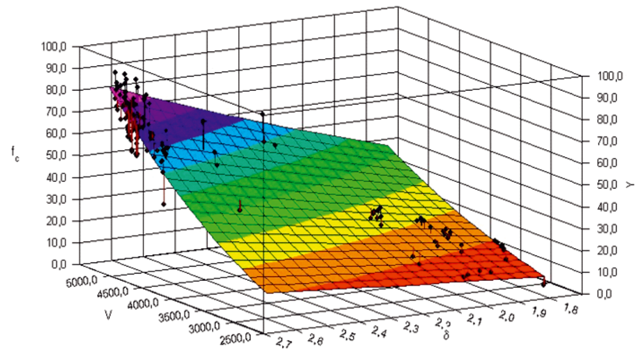
Table 9 – Results of the statistical analysis

Variable	Factor loading
Pulse velocity	0.972
Incorporate air	-0.984
Total absorption	-0.195
Void ratio	0.134
Specific gravity	0.974
Compressive strength	0.920

4.2 Evaluation of the compressive strength

At first it was possible to determine from the group of parameters measured (ultrasonic velocity, air entrainment, density, void content and absorption) those that statistically showed some influence in the values of the compressive strength.
To do so, a multivariate statistical analysis was done in all concretes to quantify the interdependence level among the parameters. A factor analysis using the principal factor method interactively and the Pearson coefficient were performed in the program XLSTAT. Then the varimax rotation is applied to facilitate the interpretation of the results that are presented in terms of factor loadings.
Variables with high factor loadings are related with the factor considered and, consequently, should present a certain interdependence with each other. Table 9 show the factor loading obtained for the factor that yielded the clearer results.
The analysis of the table puts forward that, contrary to what was expected, the void content was not a relevant parameter since it did not show a high factor loading. The same was observed for the total absorption and for the air entrainment.
On the other hand, a high factor loading and a high level of inter-

Figure 3 – Result of the prevision equation



dependence was observed for the variables compressive strength, density and ultra-sonic pulse velocity. Based on that, several mathematical regression curves were tested considering as dependent variable the compressive strength and as independent variables the ultra-sonic pulse velocity and the density. All the specimens tested at the ages of 3, 7 and 28 days from the 24 concretes were used. Figure 3 shows the graphic representation of the experimental results and of the equation that yielded the best fit.

Despite considering the results from a large number of specimens with different characteristics and ages, the equation proposed for the prediction of the compressive strength shows a high correlation degree with experimental dada (R^2= 0.927). The formulation proposed is given in equation 4.

$$f_c = 1{,}6204 \times 10^{-8} \cdot V^{2{,}4079} \cdot \delta^{1{,}7979} \qquad (4)$$

Where:

f_c = Compressive strength in MPa;

V = Ultra-sonic pulse velocity in m/s;

δ = Density of the concrete in kg/dm³

5. Conclusions

The present paper shows that the attainment of a good correlation between ultra-sonic pulse velocity and elasticity module is completely feasible. However more tests are required in order to obtain a more complete statistical analysis of the correlation derived and also to consider other independent variables that can influence the value of the elasticity module.

It was observed that the equations of CEB 90 [1] and of NBR 6118 [2] are not really calibrated to estimate the elasticity module of the lightweight HPC. Besides, it was observed that an estimation of the elasticity module with the pulse velocity equipment shows a difference of approximately 5 GPa with the new equation proposed in this paper.

Among the independent variables considered in the statistical data analysis, only the ultra-sonic pulse velocity, the density and the compressive strength show a significant interdependence degree. Therefore more studies are necessary to identify the cause of the small relevance of the void content, which was expected to have great influence over the ultra-sonic measurements.

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