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Abstract

One of the most important concrete properties for structural concrete design or re-design is the compressive strength. Furthermore, other important concrete properties can be derived from the compressive strength. This property is typically obtained by standardised crushing tests on cast cubes or cylinders.

However, cast cubes or cylinders may not be available for testing and, therefore, alternative tests need to be considered. The most reliable alternative test is the core test, which needs specimens extracted from the structure. Obviously, this is a very destructive test and other less destructive tests have been developed and deserve some attention.

Some of non-destructive or partially destructive tests were carried out by the authors on normal and high strength concrete and compared with cube/cylinder common tests and also with core tests. This paper presents results from this study. Test procedures and reliability of non-destructive tests are analysed and discussed. Conclusions are presented.

Keywords: High Strength Concrete, Concrete Standards, Surface Hardness Tests, Ultrasonic Tests

1. Introduction

Many of the concrete properties can be predicted from its compressive strength. Moreover, this property is often the only one checked for a large amount of new common concrete structures. Compliance with specification is typically achieved by means of testing a set of concrete cubes or cylinders 28 years old in accordance with standards for sampling, curing and testing [8, 9, 10, 11, 18].

The compressive tests are of outmost importance for the quality control of the concrete produced in site. However, the values from the tests can only be accepted as indicating the "potential strength" of the concrete and may differ from the actual strength of the concrete structure. The differences at 28 days are noticeable if the environmental conditions of the structures are very different to those imposed to the cubes by following the standards procedures. This has been studied and confirmed by several investigators, such as Prince and Hynes [19]. The knowledge, as close as possible, of the in situ concrete strength is, in some situations, necessary in order to estimate, for instance: the time when precast concrete members can be moved and transported, the time of prestress, removal of moulds or propping, etc. The in situ strength of concrete may be evaluated by different test apparatus presenting differences, including: accuracy, destruction to the concrete structure, speed, immediacy of results and costs.

The most destructive in situ concrete test, the compression testing of cores, is also the most reliable for the evaluation of the compressive strength of concrete. Being the most reliable method of assessing in situ strength, this method is limited in application by consideration of cost, damage and delays caused by laboratory sample preparation and testing. Sealed cylinders under temperature matched curing that reproduces the environmental conditions in the structure gives also results with similar reliability. The compressive strength can also be estimated by in situ non-destructive or partially destructive tests. However, these tests do not give direct readings of this property, and empirical correlations need to be used to estimate the concrete strength. The correlations add some uncertainties to the estimation of the concrete strength and this is a disadvantage when compared to core testing. However, this disadvantage can be overcome if proper correlations are used.

Non-destructive tests have some advantages, including: fast procedures, immediacy of results, lower costs, and low levels of damage to the structure. Interest on these tests has been growing since the sixties and this led to developments on test equipments and techniques. Test apparatus can be simple, economical and user friedly or complicate, expensive and highly specialised. They were first developed for application on normal strength concrete and recently, some of them were adapted for high strength concrete.

Some of the tests are not truly non-destructive and are designated by partially destructive. A general introduction on all non-destructive and partially destructive tests is presented in this paper and two of them, those truly non-destructive, are detailed explained. An experimental programme envolving these two kind of tests, Surface Hardness Tests and the Ultra Sonic Tests, is also presented. Ten sets of specimens corresponding to ten different concrete mixes were cast for this investigation. Concrete average strength varied from 17 MPa to 82 MPa. Each set consisted of a 550x500x170 mm normal strength concrete slab or a 750x500x170 mm high strength concrete slabs and several 150 mm cubes.

2. Remarks on NDT

Non-destructive tests are specially directed to hardened concrete [4] and they are a part of a bigger set of tests used in concrete technology. Three main test classes are generally identified, as suggested by Bungey and Millard [7] or as presented in European Standard ENV206 [9]:

1. Control tests, normally carried out by contractor or concrete producer in order to adjust mixes to ensure the quality of the produced concrete.
2. Conformity tests carried out by the inspection body to check the compliance with specifications in accordance with a pre-defined plan of sampling and testing.
3. Secondary or extraordinary tests carried out on the hardened concrete of the structure or on specimens extracted from the structure. This class of tests may be required if the conformity tests are not conclusive or if they are not available for instance, when the concrete strength of an old structure needs to be known. The long term monitoring tests of the concrete structure also fall in this category.

As far as extraordinary tests are concerned, the European standard ENV206 states (see Cause C.2.2.2):

"An extraordinary inspection is necessary:

- if severe discrepancies are dectected during a routine inspection (re-inspection);
- when there has been no production for a period of more than six months;
- on request of the producer e.g. because of changes in the production conditions;
- if requested by the certification body, given due justification"

Secondary tests can be divided into two main groups [7]:

a. Non-Destructive Tests, NDT

The non-destructive tests are normally defined as not prejudicial to the performance of the tested member of the structure. This also includes the methods that cause some surface damages to chosen locations of the structure. These tests were designated "Near to Surface Tests" by British Standards [6]. All NDT can be carried out on site with no need to extract specimens. However, the removal of finishing materials is probably necessary.

b. Tests on Specimens Extracted from the Structure

Specimens extracted from the structure are normally cores, which may be taken to the laboratory for crushing tests or for visual inspection or other physical, chemical or petrographic tests. For chemical tests, the size of the specimens is very small when compared to that required for crushing tests.

Non-destructive tests can be applied to new or old structures. For new structures, the main applications are the quality control or as additional tests to confirm the quality of materials or work. For old structures, they are normally related with the assessment the integrity and the evaluation of structural safety for future use [4]. Table 1 (next two pages) presents a list of the most common non-destructive tests.

According to British Standard, BS 1881: Part 201 [4], some of non-destructive tests cause some surface damages and may be designated by partially destructive tests.

Other important fact is the growing use of high-strength concrete. Some of the tests were developed for normal strength concrete and some investigation on the applicability of the tests to HSC is still being studied. Furthermore, the definition of "High Strength Concrete" is not concensual and can even vary geographically [1, 19]. Also a few decades before, a concrete with a compressive strength of around 35-40 MPa was already considered as "High Strength Concrete". For the current investigation, the authors considered compressive strengths over 60 MPa as High Strength.

During the last years, a large amount of investigation has been carried out on High Strength Concrete and the applicability of NDT to HSC is also being a topic under investigation. An investigation programme was carried out in both the Universities of Coimbra and Covilhã in order to study the aplicability of NDT to high strength concrete [13, 14, 15, 17]. Two of the studied tests, the Surface Hardness Tests and the Ultra Sonic Tests, are reported in this paper.

3. Surface Hardness Tests

3.1 Introduction

The surface hardness is a property that may be measured on the concrete surface and, typically, its value increases with time and with concrete strength. This observation led to the development of testing equipment and procedures to read this property and to the development of correlation curves in order to estimate the compressive strength of the concrete. However it was not possible to find a general relationship between surface hardness and compressive strength of concrete [5, 7, 16]. Despite of that, it is possible to find good correlations, if the calibrations are developed for a set of specific circumstances for a particular situation [16]. This is an interesting method not only for assessing the concrete strength but also for other applications, as explained later.

The test methods developed to measure the surface hardness may fall into two categories, early methods based on the measurement of the size of identation caused by a steel ball, and later methods based on the measurement of the height of rebound of a mass from the surface.

The most common apparatus used to measure this property is the so called Schmidt type N hammer with an impact energy of 2.2 Nm, because this is the most adequate for normal strength concrete (compressive strengths of 20MPa to 60 MPa).

Table 1 – Quick description of NDT [4]

Method	Main property directly measured by test	Main application	General applications: Quality control	Investigation on the quality of work	Mould and proping removal, prestress or load application	Comparison of the concrete quality of the structure	Evaluation of the potential durability	Investigation of damage imposed by fire, ice, chemical atack or similar cases	Surface damage	Type of equipment
Pull-out test; Lok-test type	Related with strength	Estimation of in situ concrete strength	X		X				Moderate / small	Mechanical
Pull-out test; Capo-test type	Related with strength	Estimation of in situ concrete strength	X		X	X		X	Moderate / small	Mechanical
Internal fracture test	Related with strength	Estimation of in situ concrete strength	X		X	X		X	Moderate / small	Mechanical
Break-off test	Resistance to bending	Estimation of in situ concrete strength	X		X				Substancial / moderate	Mechanical
Pull-off test	Direct tension strength	Estimation of in situ concrete strength	X		X	X			Moderate / small	Mechanical
Penetration resistance test	Related with strength	Estimation of in situ concrete strength	X		X	X			Moderate / small	Mechanical
Surface hardness	Surface hardness	Comparative survey	X		X	X	X		Very small	Mechanical
Screed test	Surface depth	Quality control of mortars	X			X	X		small	Mechanical
Dynamic response	Dynamic response	Integridade de estacas e pilares	X	X		X			none	Mechanical / electronical
Ultrasonic pulse velocity	Modulus of elasticity	Comparative survey	X	X	X	X	X	X	none	electronical
Acoustic emission	Internal cracking	Monitorização dos ensaios de carga		X			X		none	electronical
Cover depth	Layout of steel bars inside concrete	Location of steel bars	X	X			X		none	Electromagnetic

Table 1 – Quick description of NDT [4] (continued)

Method	Main property directly measured by test	Main application	General applications: Quality control	Investigation on the quality of work	Mould and proping removal, prestress or load application	Comparison of the concrete quality of the structure	Evaluation of the potential durability	Investigation of damage imposed by fire, ice, chemical atack or similar cases	Surface damages	Type of equipment
Radar	Internal interfaces	Location of voids or bars		X		X			none	Electronic
Radiography	Relative density	Location of voids or bars		X				X	none	Radioactive
Radiometria	Densidade	Controle de qualidade	X	X		X			none	Radioactive
Neutron absorsion	Moisture content	Comparation of moisture content				X	X		none	Nuclear
Carbonation depth	Concrete alcalinity	Durability survey				X	X	X	Moderate / none	Chemical
Surface initial absortion	Surface absortion	Suface permeability				X	X		small	Hydraulic
Suface permeability	Suface permeability	Suface permeability					X		small	Hydraulic
Medição da resistividade	Resistividade	Exame de durabilidade				X	X		small	Electrical
Half-cell potential	Potencial of bar electrod	Risc of corrosion in bars					X		Very small	Electrical
Strain or craking measurements	Strains, crack width	Monitoring structural movements		X	X	X	X	X	small	Óptical, mechanic or electronic
Termography	Temperature radiation maping	Structural integrity and location of voids					X	X	none	Optical, infrared
Maturity measurements	Maturity	Monitoring in situ strenght			X				small	chemical / electrical
Ressonance frequency	Dynamical Modulus of Elasticity	Quality control	X						none	Electronic

3.2 Tests Results

Table 2 shows the results of surface hardness obtained on normal strength concrete by means of a Schmidt Type N hammer apparatus, with tests being made by holding the apparatus vertically or horizontally against the concrete surface.

Table 3 shows similar results to those of Table 2 but for high strength concrete.

Table 2 – Surface hardness tests on normal strength concrete

Series No.	Compressive strength of 150 mm cubes (f_{cm})			Surface hardness test (Rebound Number - **R**)					
				Apparatus hold vertically (facing down)			Apparatus hold horizontally		
	Average value [MPa]	Standard deviation [MPa]	Coefficient of variation [%]	Average value	Standard deviation	Coeff. of variation [%]	Average value	Standard deviation	Coeff. of variation [%]
N27	23.80 (3)	2.62	11.00	29.53 (12)	1.02	3,5	29.98 (13)	1.25	4.17
N29	37.43 (4)	0.87	2.33	32.10 (12)	0.84	2.62	32.06 (14)	1.31	4.09
N30	42.33 (4)	1.74	4.11	35.,37 (12)	1.54	4.35	31.86 (14)	1.60	5.01
N31	53.18 (4)	1.94	3.65	41.57 (12)	1.49	3.59	38.84 (14)	1.93	4.96
N33	17.70 (4)	0.47	2.66	23.10 (10)	0.91	3.92	25.33 (12)	0.70	2.78

Note: the number in parenthesis indicates the amount of reading locations and for each location an average of 5 individual readings was considered.

Table 3 – Surface hardness tests on high strength concrete

Series No.	Compressive strength of 150 mm cubes (f_{cm})			Surface hardness test (Rebound Number - **R**)					
				Apparatus hold vertically (facing down)			Apparatus hold horizontally		
	Average value [MPa]	Standard deviation [MPa]	Coefficient of variation [%]	Average value	Standard deviation	Coeff. of variation [%]	Average value	Standard deviation	Coeff. of variation [%]
N34	81.94 (3)	1.12	1.37	50.82 (10)	0.84	1.64	53.52 (12)	1.16	2.18
N35	78.35 (3)	2.17	2.77	50.80 (9)	0.66	1.29	52.92 (12)	1.05	1.98
N36	49.12 (3)	1.02	2.08	42.28 (10)	0.78	1.84	40.47 (12)	1.19	2.94
N37	58.27 (3)	0.82	1.41	44.42 (9)	1.20	2.71	46.10 (12)	0.71	1.54
N38	67.77 (3)	1.56	2.30	48.60 (9)	1.01	2.09	49.00 (12)	0.93	1.91

Note: the number in parenthesis indicates the amount of reading locations and for each location an average of 5 individual readings was considered.

4. Ultrasonic Tests

4.1 Introduction

The Ultrasonic test method is a truly non-destructive test and the first reports of the application of this method to concrete appeared in the mid forties. The method is based on the measurement of the velocity of mechanically generated pulses through concrete.

The test equipment must provide a means of generating pulses, transmitting these to the concrete, receiving and amplifying the pulses and measuring and displaying the time taken. Normally, the final results are the velocity of propagation of ultrasonic pulses, in km/s.

In general, ultrasonic tests may be applied to:

1. Measurement of concrete uniformity;
2. Detection of cracking and honeycombing;
3. Measurement of changes of concrete properties with time;
4. Strength estimation
5. Measurement of elastic and dynamic modulus

4.2 Test Results

Tables 4 and 5 show the results of ultrasonic tests for normal strength concrete. Table 4 is for pulses traveling parallel to the casting direction while Table 5 is for pulses traveling perpendicular to the casting direction.

Tables 6 and 7 show the results of ultrasonic tests for high strength concrete. Table 6 is for pulses traveling parallel to the casting direction while Table 7 is for pulses traveling perpendicular to the casting direction.

Table 4 – Ultrasonic tests on normal strength concrete (parallel to casting)

Series No.	Compressive strength of 150 mm cubes (**f_{cm}**)			Ultrasonic pulse velocity (**V**) Parallel to casting direction		
	Average value [MPa]	Standard deviation [MPa]	Coefficient of variation [%]	Average value [km/s]	Standard deviation [km/s]	Coefficient of variation [%]
N27	23.80 (3)	2.62	11.00	4.371 (6)	0.081	1.86
N29	37.43 (4)	0.87	2.33	4.306 (11)	0.080	1.86
N30	42.33 (4)	1.74	4.11	4.419 (13)	0.084	1.90
N31	53.18 (4)	1.94	3.65	4.478 (12)	0.097	2.16
N33	17.70 (4)	0.47	2.66	4.076 (10)	0.072	1.78

Note: the number in parenthesis indicates the number of readings

Table 5 – Ultrasonic tests on normal strength concrete (perpendicular to casting)

Series No.	Compressive strength of 150 mm cubes (f_{cm})			Ultrasonic pulse velocity (**V**) Perpendicular to casting direction		
	Average value [MPa]	Standard deviation [MPa]	Coefficient of variation [%]	Average value [km/s]	Standard deviation [km/s]	Coefficient of variation [%]
N27	23.80 (3)	2.62	11.00	4.195 (7)	0.018	0.43
N29	37.43 (4)	0.87	2.33	4.403 (7)	0.026	0.59
N30	42.33 (4)	1.74	4.11	4.367 (7)	0.036	0.82
N31	53.18 (4)	1.94	3.65	4.476 (7)	0.012	0.28
N33	17.70 (4)	0.47	2.66	4.064 (4)	0.028	0.70

Note: the number in parenthesis indicates the number of readings

Table 6 – Ultrasonic tests on high strength concrete (parallel to casting)

Series No.	Compressive strength of 150 mm cubes (f_{cm})			Ultrasonic pulse velocity (**V**) Parallel to casting direction		
	Average value [MPa]	Standard deviation [MPa]	Coefficient of variation [%]	Average value [km/s]	Standard deviation [km/s]	Coefficient of variation [%]
N34	81.94 (3)	1.12	1.37	4.425 (6)	0.020	0.45
N35	78.35 (3)	2.17	2.77	4.574 (9)	0.067	1.46
N36	49.12 (3)	1.02	2.08	4.460 (9)	0.067	1.49
N37	58.27 (3)	0.82	1.41	4.559 (9)	0.043	0.95
N38	67.77 (3)	1.56	2.30	4.521 (9)	0.057	1.27

Note: the number in parenthesis indicates the number of readings

Table 7 – Ultrasonic tests on high strength concrete (perpendicular to casting)

Series No.	Compressive strength of 150 mm cubes (f_{cm})			Ultrasonic pulse velocity (**V**) Perpendicular to casting direction		
	Average value [MPa]	Standard deviation [MPa]	Coefficient of variation [%]	Average value [km/s]	Standard deviation [km/s]	Coefficient of variation [%]
N34	81.94 (3)	1.12	1.37	4.565 (3)	0.010	0.22
N35	78.35 (3)	2.17	2.77	4.615 (3)	0.006	0.13
N36	49.12 (3)	1.02	2.08	4.445 (3)	0.039	0.87
N37	58.27 (3)	0.82	1.41	4.524 (3)	0.086	1.91
N38	67.77 (3)	1.56	2.30	4.548 (3)	0.021	0.46

Note: the number in parenthesis indicates the number of readings

5. Discussion of the Results

5.1 Surface Hardness Tests

5.1.1 Accuracy of Assessment

The coefficient of variation of the individual readings obtained on different slab locations, with the apparatus in a vertical position facing down varied from 1.29% to 4.35%, being the average value 2.76% (see Tables 2 and 3). If the readings were separated into normal strength concrete and high strength concrete, the average values would be 3.60% and 1.91%, respectively. These values indicate a decrease of the coefficient of variation as the concrete strength increases.

BS 1881: Part 202 [5] indicates that the coefficient of variation for individual readings of harness surface tests varies from 2% to 15%, being typically around 10%. The values obtained in the investigation reported here are in the lower zone of the range presented by BS 1881 : Part 202 because of the homogeneity of the concrete achieved in laboratory conditions.

To show the variability of the results more clearly, a set of graphs were plotted. For the graphics study the readings were divided into two groups: tests on vertical direction and tests on horizontal direction. Fig. 1 shows the coefficient of variation versus rebound number and versus concrete strength and the conclusions presented above are now clear.

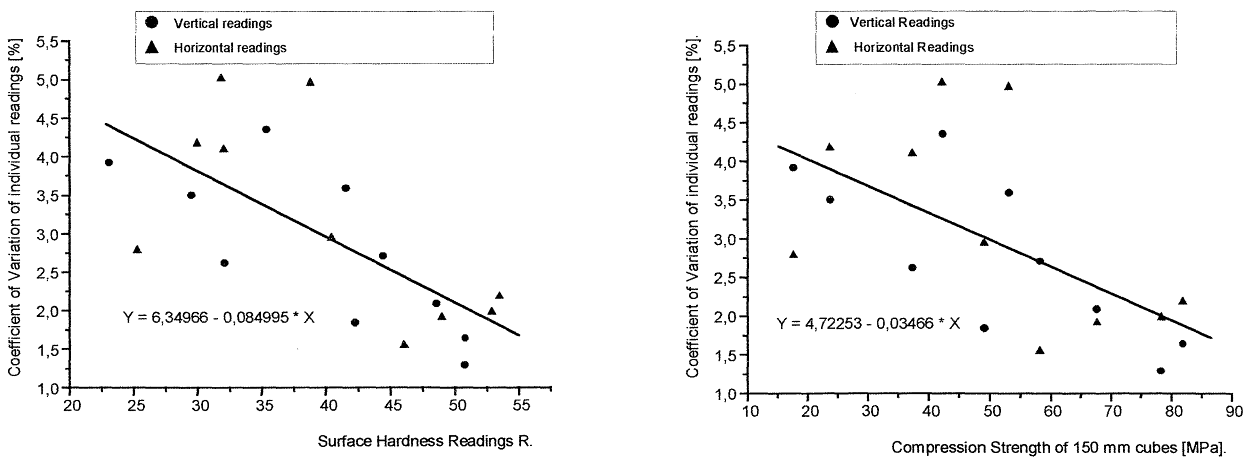

Fig. 1 – Coefficient of variation of surface hardness tests versus compressive strength

5.1.2 Relationships between Test Readings and Concrete Strength

a) Normal Strength Concrete

Fig. 2 shows two graphs of the results presented in Table 2. The results show that a relationship between compressive strength and rebound number is possible for normal strength concrete. The results are closer to the correlation line for horizontal readings. The results of the horizontal readings are more scattered because, for these tests, the Schmidt hammer was fired against the vertical sides of the concrete slabs with visually were not as homogenous as the bottom side.

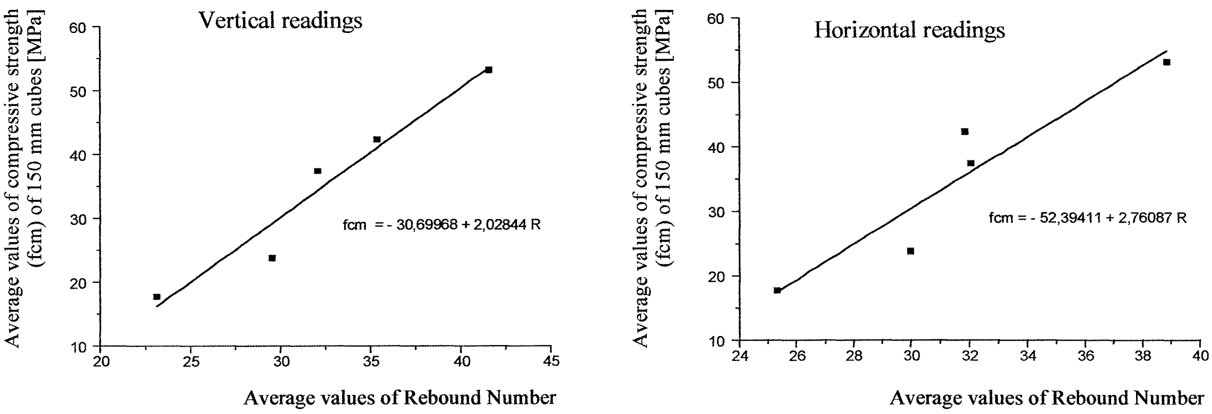

Fig. 2 – Compressive strength versus rebound number for normal strength concrete

b) High Strength Concrete

Similarly to Fig. 2, Fig. 3 shows the relationships between average compressive strength and average values of rebound number for high strength concrete. As for normal strength concrete, The results show that a relationship between compressive strength and rebound number is possible for high strength concrete. For this concrete, the results are closer to the correlation line when compared with graphs of Fig. 2 for normal strength concrete.

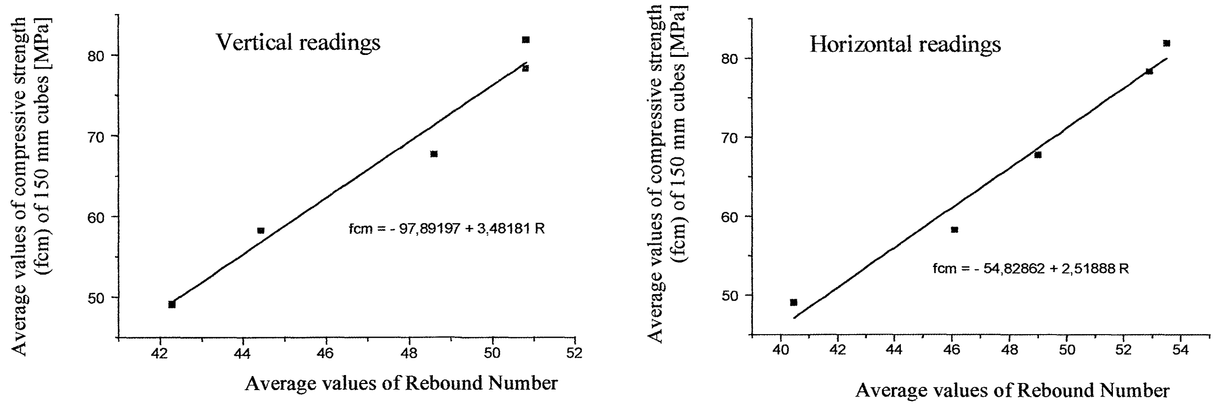

Fig. 3 – Compressive strength versus rebound number for high strength concrete

5.2 Ultrasonic Tests

5.2.1 Accuracy of Assessment

From Tables 4 to 7 some conclusions can be drawn. For instance, for both normal strength concrete and high strength concrete the coefficient of variation was typically higher for readings parallel to casting direction when compared with those perpendicular to casting. For normal strength concrete the average value of coefficient of variation equalled 0.56% and 1.92%, respectively for readings parallel to casting and readings perpendicular to casting. Similarly, for high strength concrete, those values were 0.72% and 1.12%, respectively. These figures also show that the difference between readings parallel and perpendicular to casting direction is smaller for high strength concrete when compared to those of normal strength concrete, which may indicate more homogeneity in high strength concretes.

Fig. 4 shows the standard deviation and the coefficient of variation of ultrasonic tests. Although being difficult to defend that a relationship is possible, the visual observation of the graphs shows a slight decrease of the standard deviation and of the coefficient of variation as the concrete strength increases.

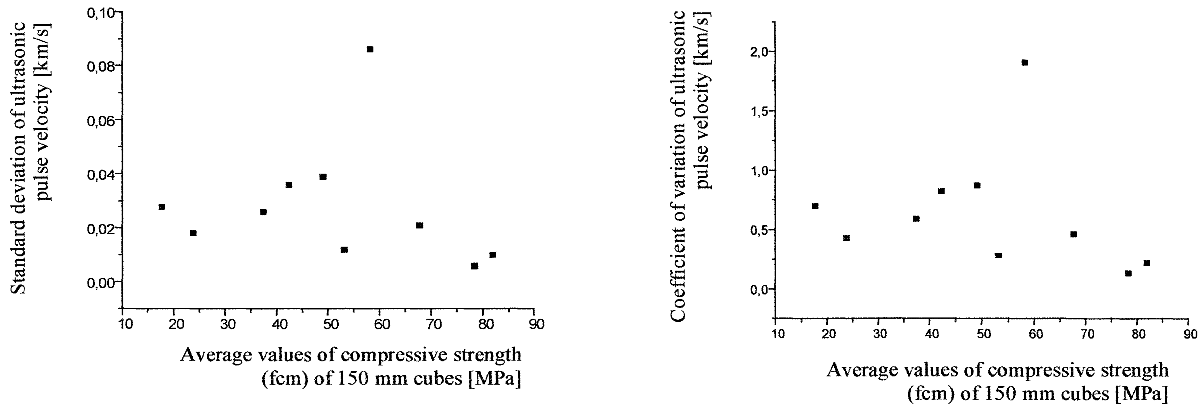

Fig. 4 – Standard deviation and coefficient of variation of ultrasonic tests

5.2.2 Relationships between Test Readings and Concrete Strength

a) Normal Strength Concrete

Fig. 4 shows the compressive strength versus ultrasonic pulse velocity for normal strength concrete. The correlation line of readings parallel to casting for normal strength concrete is not very good since the points are somehow scattered. However, the correlation for readings perpendicular to casting is better as can be seen in Fig. 5.

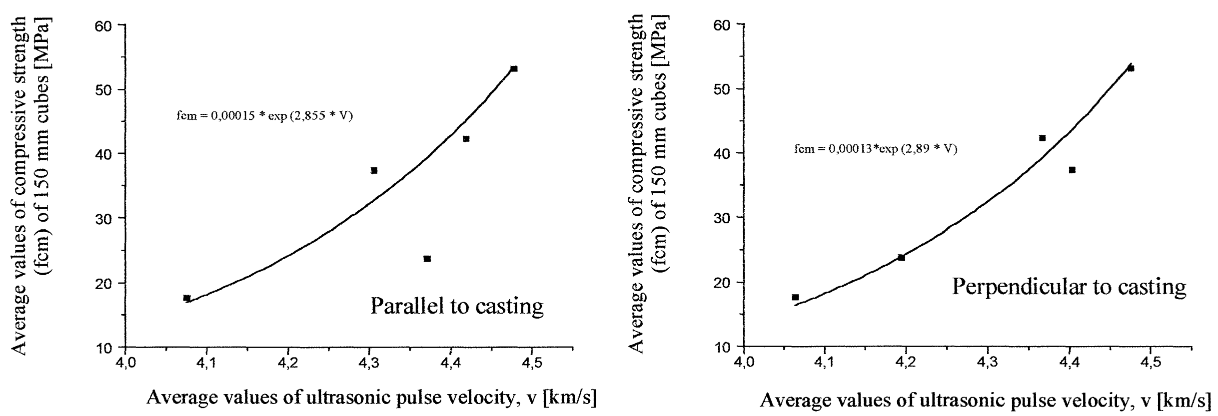

Fig. 5 – Compressive strength versus ultrasonic pulse velocity for normal strength concrete

a) High Strength Concrete

Fig. 6 shows the compressive strength versus ultrasonic pulse velocity for high strength concrete. The readings parallel to casting for high strength concrete are very scattered and a correlation line can not be found. A correlation line for readings perpendicular to casting is possible to be drawn, as can be seen in Fig. 6. However as the concrete strength increases the points became more scattered, mainly for concrete strength above 70 MPa (or velocity equals to 4.55 km/s).

Due to the exponential type correlation line, particular precautions need to be taken for pulse velocities greater than 4.55 km/s, since a small variation of the pulse velocity may lead to great variations of the concrete strength.

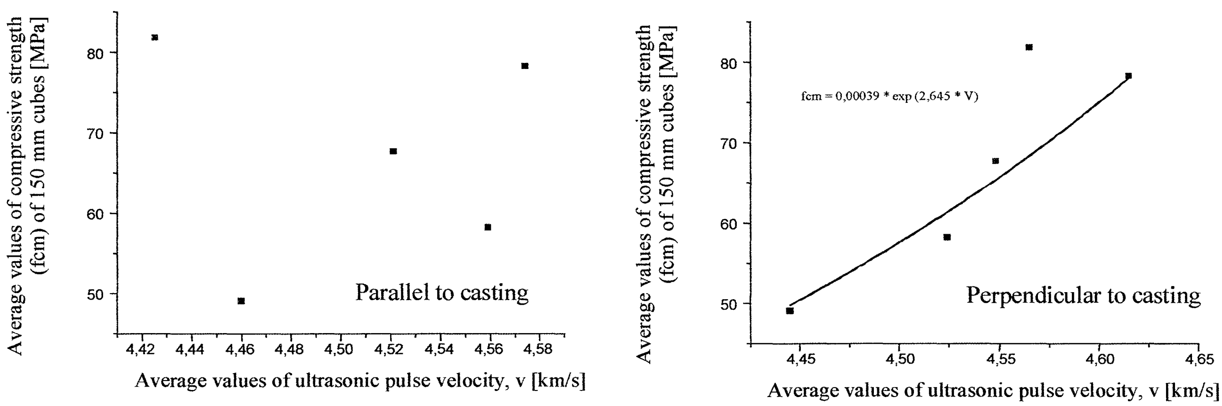

Fig. 6 – Compressive strength versus ultrasonic pulse velocity for high strength concrete

6. Conclusions

6.1 Surface Hardness Tests

As far as the hardness test method is concerned, the analysis of the results of tests carried out by of a Schmidt hammer Type N, with impact energy of 2,207 N.m lead to the following conclusions:

- The hardness test can be successfully used in high strength concrete up to 82 MPa, measured in 150 mm cubes;
- The standard deviation from the individual readings of the rebound number, which can be expected in any location of the high strength concrete up to 82 MPa was approximately constant, thus revealing typical values between 0.66 and 1.93 being the average value 1.11;
- The standard deviation is the statistical parameter which better evaluates the repetitiveness of the hardness test;
- The coefficient of variation from the individual readings of the rebound number, which can be expected in any location of the high strength concrete up to 82 MPa (evaluated in 150mm cubes) decreases as the concrete increases.

- The coefficient of variation from the individual readings of the rebound number, which can be expected in any location for a normal strength concrete between 17 MPa and 53 MPa was typically between 2.62% and 5.01% being the average value 3.90%.
- The coefficient of variation from the individual readings of the rebound number which can be expected in any location of a high strength concrete between 49 MPa and 82 MPa, was typically between 1.29% and 2.94% being the average value 2.01%.
- For compressive strength of concrete between 17 MPa and 82 MPa (measured in 150mm cubes and produced from similar materials and on the basis of the same Faury's curve, with different strengths and mixes), a good correlation between surface hardness and compressive strength of concrete was found.

6.2 Ultrasonic Tests

The experimental results presented in this paper lead to the following conclusions:

- Tests indicate a slight reduction of the standard deviation and of the coefficient of variation, when both the compressive strength and the ultrasonic pulse velocity increase.
- The coefficient of variation of the individual readings of ultrasonic pulse velocity in a location of a good quality surface of high strength concrete, between 17 MPa and 53MPa (referred to 150mm cubes) showed an average value of 0.56% in readings on moulded faces.
- The coefficient of variation of the individual readings of ultrasonic pulse velocity in a location of a good quality surface of concrete strengths between 49 MPa and 53 MPa, showed an average value of 1.12 in readings on moulded faces;
- The maximum coefficient value of variation of ultrasonic pulse velocity obtained in different locations (test slabs), among the tested concrete (with the same materials and different A/C values) was of 2.16%.
- It is possible to establish a correlation between the ultrasonic pulse velocity (by direct readings between moulded faces) and compressive strength (between 17 MPa and 70 MPa), when the variable is the ratio water/concrete (in mass) and are kept constant some parameters, including: the maturity , the type of materials and the reference Faury's curve;
- The value of pulse velocity obtained by direct reading, involving a moulded face and a non-moulded face diverged in a large extent from the direct reading among moulded faces;
- The correlation between high strength and ultrasonic pulse velocity obtained by direct readings involving a moulded face and a non-moulded face showed great dispersion of results.
- The correlation curve between the ultrasonic pulse velocity and compressive strength is an exponential type curve which seems to be more acceptable than a straight, as proposed by Bungey and Millard [24];
- For concrete strengths from 45 MPa to 50 MPa and possibly up to 82 MPa, the correlation curve between the ultrasonic pulse velocity and compressive strength of concrete tends to a straight when granitic aggregates are used;
- The correlation between the ultrasonic pulse velocity (direct reading on moulded faces) and the compressive strength of concrete might indicate a loss of reliability for compressive strengths above 70 MPa.. This can be caused by the exponential type of the correlation. Any slight variation of ultrasonic pulse velocity above 4,55 km/s would result on a great variation of the value of the compressive strength of concrete.

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