



Ultrasonic Pulse Velocity Analysis in Concrete Specimens

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Abstract

Concrete is a basic material used for the great amount of engineering projects. The concrete performance is influenced by some building variables, such as: the water/cement ratio, the aggregate type and size, the humidity and the cement type. These variables affect directly the compressive strength and make difficult the identification of the concrete properties. Focusing on it, the ultrasonic tests allow to estimate a correlation between the variables and the compressive strength. Once concrete is a heterogeneous material, the interpretation of the relation between the strength and the Ultrasonic Pulse Velocity (UPV) becomes complex. Aiming to understand how some parameters influence the UPV, this work studied different concrete types, with different characteristics, manufactured with portland cement and various types of aggregates. The data had been analyzed aiming to establish models to understand how the results of UPV are affected by variations at concrete conditions. The results show that it is possible to understand how the test condition variations affect the UPV outputs. This study indicates that UPV gives an important result of decision-make about the conditions of concrete structures. It can be concluded that, by means of UPV, it is possible to contribute with the deterioration control and concrete structures quality.

1. Introduction

In the last few decades, the application of Nondestructive Testing (NDT) in civil engineering has becoming a subject of interest in various countries. The concrete can not be considered as an eternal material once maintenance is needed to guarantee its life-time. The lack of maintenance observed in some structures leads to some pathological manifestations with significant intensity ⁽¹⁾. NDT do not only allow the evaluation of aged and spoiled structures; they also can be used in quality control of new structures. Civil engineering is a field in which the use of the NDT can be developed. They also can become an important tool to assist the professionals considering the quality control of new buildings.

The NDT methods are used in a great amount of researches. This occurs because these methods do not affect the appearance and the performance of the analyzed structures. The method allows doing the tests at the same place, making possible a continuous

monitoring in the structures and a determination of possible variations during a period of time. Once the structures are monitored, the life-time can be predicted, and consequently, the treatment and the recovery become more easy and economic. The NDT application in Brazil has grown during the last years. However, the routine procedures are not well known in the civil engineering area.

The NDT methods are not reliable to measure the structure strength, but they are useful to analyze the concrete properties and to determine its homogeneity. The correlation between the NDT and the structure strength can be established. The correlations are particular for a certain type of concrete and must be used with caution.

Concrete properties can vary considerably depending on the nature and proportions of its materials, the construction methods and the loading and environmental conditions. In order to prevent and control the concrete deterioration, it is interesting to establish continuous monitoring strategies, which might be a powerful tool to increase the service life of concrete. This implies the development of control methods which are able to determine the quality and the condition state of concrete. UPV methods can play an important role in this area, since they allow us to monitor the density and homogeneity of the material, providing information about the strength evolution and about the existence of internal flaws and defects.

The UPV methods have been used in inspection operations and monitoring of concrete structures. This test allows to measure and to control a series of basic parameters to determine the concrete quality. However, interpreting the result of this type of test need to be made in a criteriously form and demand a specific knowledge of the influential factors. In order to collaborate with the development of the models that consider these factors, it was decided to carry a study aiming to analyze how the cure process influences the ultrasonic readings.

Using the UPV, it was possible to collect results of concrete specimens, leading to an opportunity to analyze how the cure process of concrete affects the readings. This analysis is important for concrete durability prognostics and can be useful considering the economic aspect.

2. Concrete Evaluation considering Nondestructive Testing

The 1990 Model Code provides comprehensive guidance to the scientific and technical developments that have occurred over the past decade in the safety, analysis and design of concrete structures. According to this code, a concrete structure must be projected, constructed and operated in such a way that keeps its security, functionality and acceptable appearance during a period of time, without the necessity of raised costs of maintenance and repair, CEB⁽²⁾.

To extend the life-time of a structure, it is necessary to characterize the material. In order to cover the project necessities about the strength and concrete structures life-time, it is interesting to use an evaluation system to check the conditions and estimate the homogeneity and compacity of concrete. The use of NDT is an attractive strategy considering this context. NDT tests allow making an analysis about the structures conditions, with no damage caused on that.

NDT has been defined as those test methods used to examine an object, material or system without impairing its future usefulness. NDT methods have developed from a laboratory curiosity to an indispensable tool of production. These methods are used to

check variations in structure, changes in surface, the presence of cracks or other physical discontinuities, to measure the thickness of materials and to determine other characteristics of industrial products ⁽³⁾. NDT determination of materials properties is becoming increasingly important in design and life assessment consideration of components and systems ⁽⁴⁾.

The application of NDT in civil engineering has become a subject of interest in various countries. NDT methods not only allow the evaluation of aged and deteriorated structures, but can also be used for the quality control of new structures ⁽⁵⁾. NDT methods are very important components of inspection procedures of infrastructure objects: bridges, highways, tunnels, and other civil and industrial structures ⁽⁶⁾.

One of the main advantages of NDT methods is that they do not affect the appearance or the functioning of the structures under analysis. Furthermore, data can be periodically collected from the same test points, making possible the control of variations over time. This systematic monitoring scheme might help to make an early detection of possible defects and degradation mechanisms, prompting quick interventions that are more economical and efficient.

Some NDT equipments allow verifying the behavior of concrete structures since the initial ages. This is the case of UPV tests, which allows inquiring the initial conditions, monitoring the characteristics variation during the time, and making possible to estimate the concrete strength. This test is used to detect some imperfections in homogeneous materials and it also provides good results. The UPV is suitable for evaluation of composite material, such as the concrete. However, it is necessary to know the influence of the variables that affect the concrete characteristics.

This study inquires the interaction between strength and UPV for a molded series of concrete cylinders specimens. The compressive strength is the most used control property to analyze the concrete quality. The idea is to determine where the ultrasonic measures of the tests can be used as a parameter to control the strength evolution.

2.1 Ultrasonic Pulse Velocity

Among the available methods of NDT, the UPV methods can be considered as one of most promising methods for evaluation the concrete structures, once it makes possible an examination of the material homogeneity. It is possible to obtain a total control of a structure, using the properties variations with the time. Using the analysis of the propagation variations of ultrasonic velocity wave, it is possible to verify the compacity or detect heterogeneous regions in the concrete.

These methods allow the examination of material homogeneity and also turn easier the diagnosis of defects. The UPV methods make possible the continuous evaluation of concrete conditions during the entire structure service life. The UPV results can be used for diagnosis, prognosis and quality control.

The method is based on the propagation of a high frequency sound wave which passes through the material. The speed of the wave varies in function of the density of the material, allowing the estimation of the porosity and the detection of discontinuities. The idea is to project the sound inside a material and measure the time necessary for the wave to propagate through it. Once the distance is known, it is possible to determine the average pulse velocity, which will depend on several factors such as the nature of the material and the presence of water in the pores, among others.

The method is normally based on the use of portable equipment, composed by the source/detector unit and the surface transducers, which works in the frequency range of 25 to 60 kHz⁽⁷⁾. The ultrasonic pulses depend on the density and elastic properties of the material.

The methodology of UPV is based at time monitoring of pulses in a section of the object. The UPV will depend on the density and the elastic properties of the material in study. The quality of many materials of construction is related with its rigidity, the measure of the UPV can be used to measure the concrete structures quality, estimate the mechanical properties, the compressive strength and the modulus of elasticity⁽⁸⁾.

The tests begin when an ultrasonic pulse is generated and transmitted for an electro-acoustic transducer, placed in contact with the surface of concrete. After to pass the concrete, the vibrations are received and converted by the electro-acoustic transducer. The passed time between input and output of the wave is measured with precision of at least 0,1 μs ⁽⁹⁾.

The sounds which are produced at one environment might be reflected or reverberated into the surrounding surfaces, and these sounds can still be transmitted to other environments. Phenomena like this are the basis of ultrasonic methods in materials⁽¹⁰⁾. Sounds extremely acute can pass unperceived for the human ear. That happens for vibrations with very low frequencies, until 20Hz (infra-sound) or with very high frequencies, above of 20 kHz (ultrasound). The ultrasonic methods work in the high frequencies. The sound is projected at one material and measures the UPV, which depends of the material nature, the porosity, and the presence of emptiness or water in the pores system, between others factors.

The UPV tests are used to characterize a material, to determine the integrity and to measure other physical properties that influence the wave propagation. They are a useful technique for quality control and can be used for detection of defects, thickness measurement or materials characterization of concrete, as explains ASTM E 114-95⁽¹¹⁾.

In order to use the UPV in concrete, the Brazilian Standard NBR 8802 establishes some procedures to make the tests. Normally, the UPV is used in order to verify the concrete uniformity, to detect internal imperfections, to evaluate the depth of imperfections, to estimate the deformation moduli and the compressive strength and to monitor the characteristics variations of concrete throughout the time⁽¹²⁾.

The test is sensitive to changes in concrete density, constitution and soundness. Once there are various intervenient parameters, the results tend to be used in comparative terms. It is also used to check the homogeneity and to find spots that have different properties than the surrounding areas. It may also be used to measure the thicknesses of the several layers of a composite material⁽¹¹⁾.

The UPV can also be used to explore the relation between the concrete qualities with the compressive strength. The main idea is to explore the fact that ultrasonic velocity waves are function of the density of the material and that they are correlated with the compressive strength. The relation is not always trustworthy once there are a lot of variables that affect the concrete strength, such as: the water/cement ratio, the size and type of aggregate, the molding procedure, the sample size and the cement type.

UPV method is effectively applied to monitoring some procedures of concrete curing. It allows controlling important parameters such as strength, elasticity module and shrinkage of concrete (both in laboratory and in-situ). The use of UPV methods is quite useful to investigate concrete structures once it allows the monitoring of the material characteristics along its service life. Using ultrasonic data, it is possible to determine the

concrete uniformity, to control its quality, to accompany its deterioration and, by using a comparison with control specimens, to estimate its strength.

One limitation of the technique, however, is that the relationship between ultrasonic and compressive strength values is affected by several factors, such as: the concrete age, the aggregate type and proportion, the carbonated depth, etc. Furthermore, the evaluation of ultrasonic is a highly specialized and complex activity which requires careful data collection and expert analysis. The possibility of estimating the compressive strength, which is the main structural parameter, from an NDT test, is very alluring. Therefore, there is a steady interest in establishing useful correlations between UT and compressive test results.

3. Concrete Analysis through Ultrasonic Pulse Velocity

Concrete is widely used in civil constructions. This fact explains the studies on its properties. Traditionally, the property used to analyze the quality of this material is the compressive strength. The possibility of estimating the compressive strength, the main structural parameter, from an UPV test, is very alluring. Therefore, there is a steady interest in establishing useful correlations between ultrasonic pulse velocity measurements and compressive test results. The problem is that there are a lot of variables that might affect this correlation. The water/cement ratio, the size distribution of the aggregates, the humidity and the cement type, for example, affect the compressive strength and the density.

UPV methods can be considered as one of most promising methods for evaluation the concrete structures once it makes possible an examination of material homogeneity. The total control of the structure is also possible by using the variations of properties with the time. Analyzing the ultrasonic velocity wave propagation variations, it is possible to verify the compacity of the structure or detect heterogeneous regions. The ultrasonic test methodology in concrete is based on the fact that the propagation time expresses the density of the material, which might be correlated with the mechanical properties, such as the compressive strength and the elasticity module⁽⁷⁾.

The tests can also be used to explore the relation between the concrete qualities with the compressive strength. The main idea is to explore the fact that ultrasonic velocity waves are a function of the material density, which is correlated with the compressive strength. The relation is not always trustworthy once there are a lot of variables that affect the concrete strength such as the water/cement ratio, the size and type of aggregate, the molding procedure, the specimen size and the cement type. UPV techniques can also be applied in order to evaluate the uniformity of the concrete in a structure⁽¹³⁾. The relation between UPV and concrete density justify the use of UPV for the evaluation of the concrete, but it is necessary to be aware about the limitations of it.

The main problem is that the same characteristics that affect the strength (age, porosity, composition and cure) also affect the UPV. This correlation is not simple and it depends on some factors. Similar concrete strengths sometimes have different UPV. These differences make difficult the interpretation of UPV results. An important factor is that the UPV allows making the tests in the same place as the one made before.



Picture 1. UPV at Concrete.

4. Experimental Design

Five variables had been considered in this research: water/cement ratio (w/c); age; aggregate type, cure and air incorporator.

The w/c ratio is the main parameter which causes direct influence in the concrete strength. The ratio between cement and aggregates has also a strong influence in the definition of the pores structure and in the material compacity. This study analyzed w/c ratios of 0,35; 0,50 and 0,65.

The period of cure is a variable that have relative importance to the concrete strength considering the advance of the cement hydration. To evaluate if the UPV is sensitive to these changes, some tests were made in cylinders specimens considering the periods of 3, 7, 28 and 56 days. Once finished the UPV test, the specimens were submitted to the strength test.

The experimental analysis also uses basaltic, granitic and limestone aggregate. The intention is to check if the differences of compacity and affinity with the cement matrix of these materials would cause sensible variations at the UPV results.

Another variable of study was the type of cure of concrete. This variable can affect the superficial porosity, the strength and the permeability. Cylinders specimens were submitted to three types of cure: immersed, placed in humid chamber and placed in the laboratory environment.

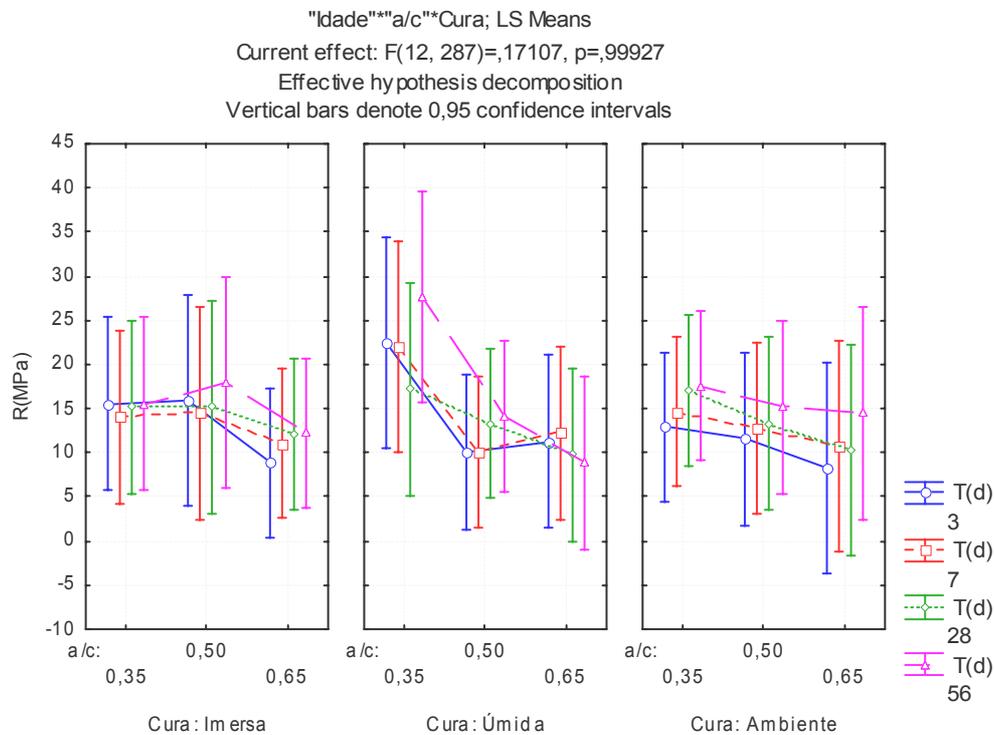
The last variable of study was the air incorporation. The use of incorporators causes some emptiness in the material structure. These concrete lacks become obstacles in the propagation of UPV. The goal is to measure the increment of the emptiness that affects the UPV. Considering this, some air incorporators were used in a proportion of 0,75% and 1,50% in relation to cement weight.

Once there are a large number of variables, a factorial planning of experiments was carried out to optimize the number of moldings. Three levels for each variable were established, codified as 1, 0 and -1. After the reduction statistics of the variable combinations, the traces were established.

4. Statistical Analysis

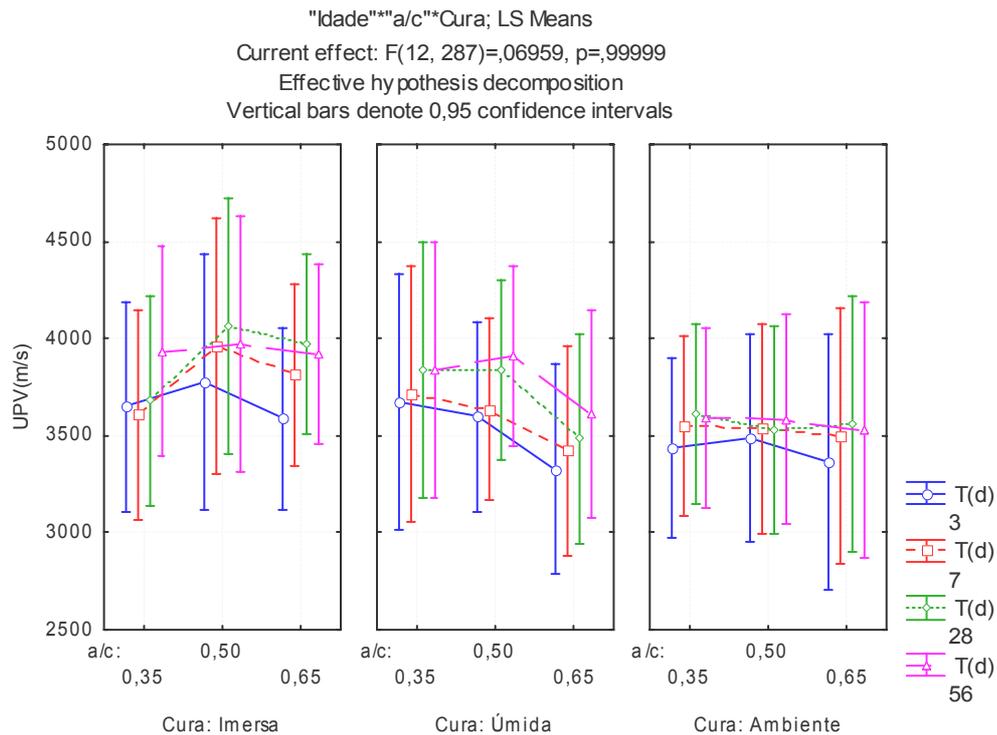
It is possible to observe, in the pictures 2 and 3, the influence of the cure type at the strength and UPV of concrete. The pictures show that both parameters are influenced by cure, however in different ways. The evolution considering the time is observed. This can be explained as a function of the cement hydration during the time.

Picture 2 shows that cure affects concrete strength. It is observed clearly that, considering the immersed cure, the results of 3 days with w/c ratios of 0,35 and 0,50 are higher values than those for 7 and 28 days. This fact can be explained by the cement type (CPV-ARI) used in this study. In regard to the humid cure, it is noted that tests with w/c ratio of 0,35 at 28 days have lower expected results. However, it is observed that when the w/c ratio is 0,65, and considering the initial ages, the values are superior than those in advanced ages. Finally, in regard to the environmental cure, a coherence of results is observed.



Picture 2 – Influence of cure in strength.

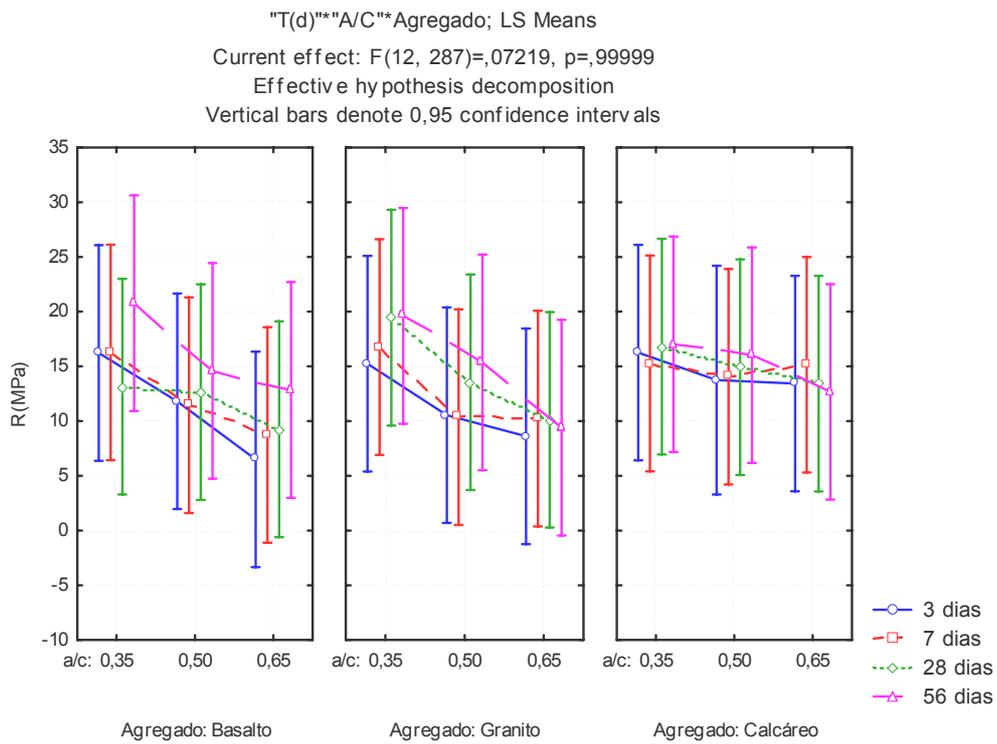
Picture 3 shows the influence of cure in the UPV data. It is clearly observed an increment of the UPV with the period of time. However, in some results (immersed cure), the evolution of the UPV was not noted. The experimental results from the cylinders specimens with w/c of 0,35 at the ages of 7 and 28 days remained the same values of UPV tested in 3 days. This can be explained by the fact that the cement type used was the one with high initial strength. This cement contributes to produce high values of strength at initial ages. Another factor that can contribute is the delay of carrying the UPV tests, since the cylinders specimens are removed from the cure system. This factor does not occur in the other cure types and, consequently, it is observed an adequate behavior of tests results.



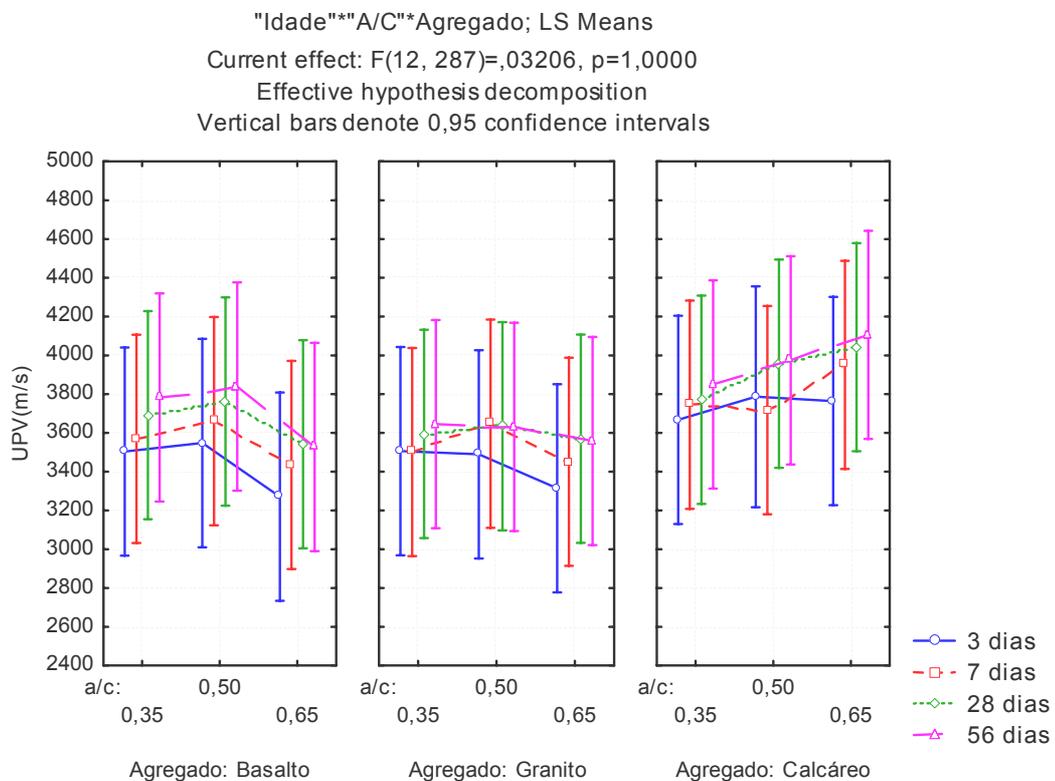
Picture 3 – Influence of cure in UPV.

Pictures 4 and 5 show the growing trend for different aggregates types, in regard to strength and UPVs. Picture 4 shows the influence in concrete strength. It is noted that the aggregate type contributes significantly. Difference from the values of compressive strength for the aggregates types can be confirmed. One consideration about this analysis is that the compressive strength of the rocks for the production of the concrete is different. It is possible to visualize that, when it is used w/c ratio of 0,65 and limestone aggregate, there is a high strength variation. Considering the ages of 28 and 56 days, the results do not followed the same trend of evolution of the resistance showed at other ages.

Picture 5 shows the influence of aggregate type in the UPV. It can be noted that the basaltic aggregate present the best results in evolution of UPV. The granitic aggregate has normal values of UPV. It is observed in the most of the cases an increase of strength with a reduction of w/c ratio. In regard to the age of tests, it did not follow an increase of the UPV, but a reduction. The limestone aggregate presented the highest discrepancy, in UPV terms; with an increase of concrete strength, a reduction of UPV have occurred.

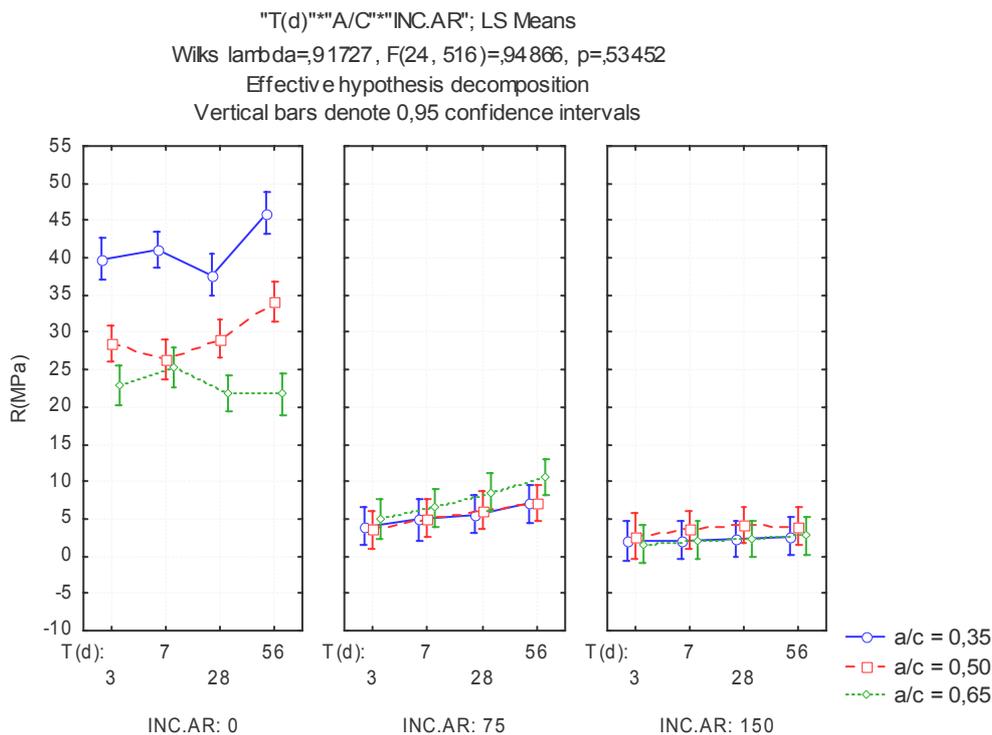


Picture 4 – Influence of aggregate in strength.



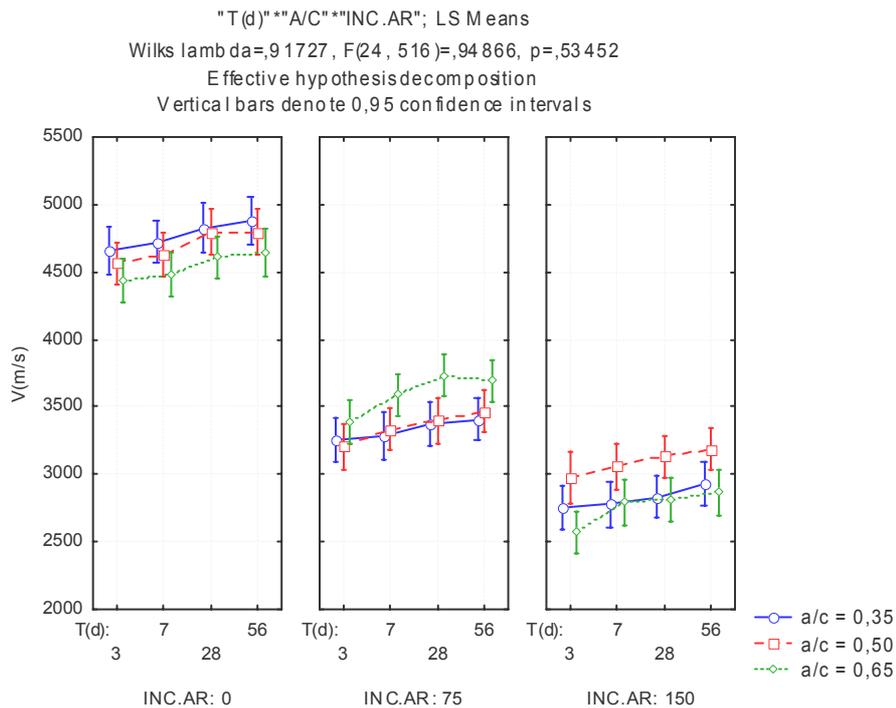
Picture 5 – Influence of aggregate in UPV.

Pictures 6 and 7 show the influence of emptiness inside the concrete for strength and for the UPV. As higher the percentage of emptiness becomes, the strength and the UPV decrease, and the values decrease throughout the age. Picture 6 shows the influence of the air incorporator additive in the concrete strength. A small percentage of 0,75% of air incorporator have a great influence in concrete strength. The use of this additive in the concrete has a significant reduction in the strength. This can be explained by the fact that the additive introduces air micron-bubbles distributed homogeneous inside the concrete. When it is used 1,50% of air incorporator, the reduction of the values of concrete strength becomes more significant. This reduction, however, did not have the same ratio as the first one, once the very small values of strength have already been reached.



Picture 6 – Influence of air incorporador in strength.

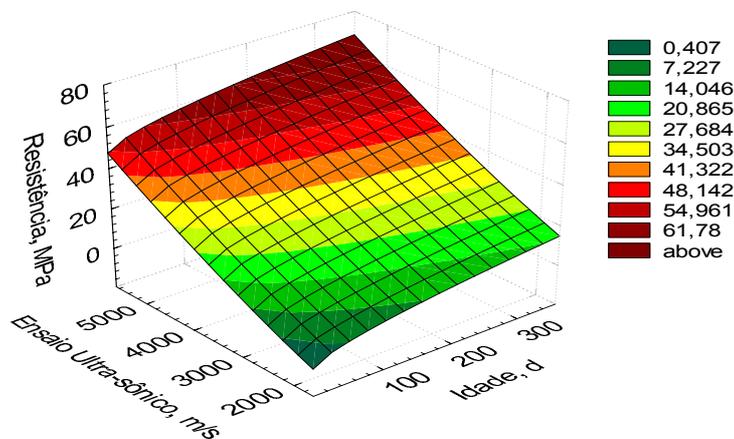
Picture 7 shows the same trend in relation of UPV. The increase of emptiness causes a reduction of the UPV. This factor can be observed clearly in the picture, where a percentage of 0,75% of incorporator causes the reduction of the UPV. It is important to mention that this is close to the minimum values of UPV for concrete. This concrete is classified as a regular concrete in quality terms. When it is analyzed the UPV data and concrete strength together, it is noted that this concrete is similar to a concrete with low quality.



Picture 7 – Influence of air incorporator in UPV.

By using the software Statistica 6.0, a nonlinear statistical model was generated considering a strategy of traditional modeling. The nonlinear estimative is an appropriate procedure to estimate relationship between one dependent variable and a list of independent variables. In this case the dependent variable was the concrete strength. The correlation coefficient R^2 will explain the relationship between the analyzed variables. Values next to 1 indicate that the variability is almost completely explained by the model. Focusing on these simulations and representation of the phenomena, the R^2 is 56% (Figure 8). The traditional statistics simulation does not explain the relation between inputs and the compressive strength.

Modelo: $R=b_1+I^{**}b_2+b_3/UT^{**}b_4$
 $R=(-19,36615)+I^{**}(0,524125)+(0,000552)/UT^{**}(-1,353024)$



Picture 8– Statistics Simulation – Statistica 6.0.

5. Conclusions

Focusing on the necessity of getting concrete structures with quality and durability, the NDT research aims to understand the capacities and limitations of tests. The studies on UPV follow this trend. The concrete is a heterogeneous material and the interpretation of the relation between strength and UPV is very complex.

The amounts of emptiness, the w/c ratio, the aggregate type and others variables affect the concrete strength. The results show that there is a good correlation between strength and UPV. The data indicate that the variation of the cure conditions and aggregate type can generate effects that are more sensible in the UPV than those generated in experimental strength. The presence of air incorporator affects considerably both of them.

The results show that it is possible to understand how the variations of tests conditions affect the results of UPV, which can lead into a decrease of the errors considering the strength estimation. This step is possible by using the quantification and qualification of the laboratory data.

This study indicates that UPV tests are sensitive tools to analyze variations in homogeneity and density of the concrete. UPV tests can supply important data about decision-making of concrete conditions. It can be concluded that, by means of UPV, it is possible to contribute with the control of deterioration and concrete structures quality.

References

1. *CONCRETO: Ensino, Pesquisa e Realizações*. Organização: G. C. Isaia. São Paulo: IBRACON, 2005. pp 1109.
2. COMITÉ EURO-INTERNATIONAL DU BÉTON. *CEB-FIP Model Code 1990*. London: Thomas Telford, 1993.
3. ASNT, "Introduction to Nondestructive Testing". *The American Society for Nondestructive Testing*. <http://www.asnt.org/>, 2006.
4. BRAY, D. E., STANLEY, R. K., *Nondestructive Evaluation – A Tool in Design, Manufacturing, and Service*. Boca Raton: CRC Press, Inc., 1997.
5. Nogueira, C. L., "Análise Ultra-Sônica da Distribuição dos Agregados no Concreto através de Wavelets", *Proceedings of the XXI Congresso Nacional de Ensaaios não Destrutivos*, ABENDE (Eds.), 2002.
6. Lorenzi, A., Nesvijski, E., Sarkis, P., Sarkis, J., "Infrastructure NDT Monitoring Using Inspector-Computer Interface", *Proceedings of the ASNT Fall 99 Conference and Quality Testing Show*, ASNT (Eds.), 1999.
7. POPOVICS, S., *Strength and Related Properties of Concrete - A Quantitative Approach*. Nova York: John Wiley and Sons, 1998.
8. MENEGHETTI, L. C., PADARATZ, I. J., STEIL, R. O., 'Use of Ultrasound to Evaluate Concrete Strength in the Early Ages'. *Proceedings of International Symposium on Nondestructive Testing Contribution to the Infrastructure Safety Systems in the 21st Century*, pp 42-47, 1999.
9. NEVILLE, A. M. & BROOKS, J. J. *Concrete Technology*. 6. ed. Singapore: Longman Singapor Publishers Pte, 1997.

10. ANDREUCCI, R., *Ensaio por Ultra-som – Aspectos Básicos*. São Paulo: 2002. 59p. Disponível em: <<http://www.abende.org.br>>. Acesso em: 10 nov. 2002.
11. ANNUAL BOOK OF ASTM STANDARDS, *Standard Practice for Ultrasonic Pulse-Echo Straight-Beam Examination by the Contact Method*. Vol. 03.03 Nondestructive Testing. West Conshohocken: ASTM E 114-95, 1995, 920 p., p. 12-15.
12. NBR 8802: *Concreto endurecido – determinação da velocidade de propagação da onda ultra-sônica: método de ensaio*. Rio de Janeiro, 1994.
13. LANDIS, E., PETERSON, E., SELLECK, S., SHAH, S., LI, Z., ZDUNEK, A., PRINE, D., *Developments in NDE of Concrete*. Northwestern University Center for Advanced Cement-Based Materials e BIRL Industrial Research Laboratory. Disponível em: <<http://iti.acns.nwu.edu/pubs/landis.html#pulse>>. Acesso em: 20 de nov. 2002.