COB09-2472 - ANALYSIS OF RESISTANCE'S RELIABILITY TO COMPRESSION OF ARMORED CONCRETE USING HARDNESS TESTS BY SCLEROMETER AND PINS PENETRATION.

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Abstract:
We intend in this article to highlight of the statistical reliability of relative hardness test by using a sclerometer, in comparison with pins drilling, to verify concrete's resistance to compression. Our aim is to compare the results of the relative hardness essay against the rupture's tests of reinforced concrete body's proof, carried out in labs of technological control of armored concrete, by utilizing a press. Armored concrete's resistance determined by body's proof in labs allows the knowledge of concrete's resistance by using testimony of fresh concrete, waiting for its old age. One searchs to know, fundamentally, what is the resistance of 28 days old concrete, to compare it against the considered resistance of structural pieces on carried out calculations pieces. Concrete's resistance growing to compression occurs significantly up to 28 days. This resistance continues to grow expressively to the maximum of 5% (five per cent) for ages equal or more than 60 days as carried out essays confirm. Sometimes the resistance determined by the body's proof do not reach the expected value. So, it is necessary to know concrete's resistance on the structure. Practically there are three processes which present better results to obtain potential resistance of structure's concrete: extraction of concrete's samples, pins penetration and hardness test through sclerometer. Searching to stablish a more exact correlation with the results of pins penetration essays and the ones of hardness tests by sclerometer, and the results of compression resistance tests on bodies' proof carried out in labs, we have sets of values obtained through the molding of concrete's bodies' proof to which we apply hardness tests and pins penetration, which will be analysed in the process.

Keywords: *reliability; Armored or Reinforced Concrete; Experimental analysis*

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1. Introduction

Sclerometry and pin penetration technological tests are quite used for two reasons: Firstly, when the rupture results from the concrete tests performed in lab through concrete compression press are below those specified by the job's calculating engineer, and secondly, when the result obtained in the concrete resistance test samples performed in lab are good, i.e. when compression resistance result is equal to or higher than what the calculation engineer specified, but in the construction job in question the concrete presents problems such as cracks or abnormal bending, leading to doubts as to the concrete’s quality or resistance.

In the two-abovementioned cases, it is essential to confirm the compression resistance of the concrete used in the construction’s structure, which is possible through sclerometry and pin penetration tests separately or conjunctly, as we propose herein.

There is a great advantage in adopting these two tests, namely not damaging the concrete tested and therefore preventing any loss to the structure, and therefore non-destructive in nature. However, the disadvantage is in reference to the credibility of their results in the Civil Construction market.

In view of the above, we propose herein, in addition to the implementation of the tests, their reliability analysis in order to study the tests results from the sclerometry and pin penetration in order to verify concrete compression resistance by means of analysis and comparison of several data collected in lab through concrete compression tests.

There are also cases in which the given resistance of the tests samples fails to reach the expected value after the aging process performed in the lab, leading to the need therefore to have knowledge of the concrete in the structure itself, which is possible by means of the abovementioned tests.

The sclerometry and pin penetration tests deserve special consideration in terms of statistical reliability in comparison with the results obtained in the same with sample rupture tests performed in concrete technology labs.

2. Bibliographic Review

2.1. The Sclerometry Test

The need to obtain more information on the resistance of concrete in order to evaluate the safety of structures over the years led to the creation of the sclerometer, a device employed in the sclerometry test.

The sclerometer was created in 1948 by Swedish Engineer Ernest Schmidt, and has since then been used quite regularly by engineers and architects. The test consists in determining concrete surface hardness by shooting a metallic rod against the material's surface, determining the sclerometric index. Concrete resistance is obtained in the abacuses, supplied by the equipment manufacture, which correlate the sclerometric index and its probable resistance for different ages.

The sclerometric tests method, also referred to as surface hardness test, is relatively cheap and has been used for several years with relative success, being therefore of good reliability. As such method restricts to concrete surface analysis, its use is relatively limited in solid structures. In addition, the method should be used in structures relatively new [Minor *et al.* 1988]. To be applied in older structures, it is necessary to remove the test bodies and conduct correlation analysis between compression resistance and sclerometric exam results [Malhotra and Carino 1991].

This study demonstrates that the sclerometry tests can be use with optimum precision to estimate concrete resistance, proposing an adjustment coefficient for the result obtained due to the age of the analyzed material.

2.2. Pin Penetration Test

The evolution of the production control of concrete structure's industrial activities in the production process and during the service life imposed the need for tests to verify the quality of structures.

Structures presented pathological problems such a the deterioration of concrete or mechanical resistance below design specifications, undergoing tests to evaluate resistance or estimate real resistance capacity, and therefore determining the need for repair or even demolition.

In general, the tests used in the evaluation of the resistance of structures or their elements is based on inadequate behavior, in change of use, external action (fire, earthquake, etc.), unforeseen overload, impact from accidents, or deterioration itself from the action of time (aging) due to lack of maintenance.

One of the tests to evaluate concrete’s mechanical resistance is the pin penetration test, which was not greatly welcomed in the beginning due to the few publications and sclerometry method introduction in the international market.

In the middle of 1933, Professor B. Skramtayev studied in the Soviet Union a process in which concrete was shot on the surface by a firearm from a distance of 6 to 8 meters, followed by measurement of the small crater created from the projectile's impact, enabling the creation of a simple correlation formula for this column and the compression tension of the concrete examined. (Vieira, 1978).

Russians Polyakay and Magnitostroy suggested a new resistance evaluation technique by embedding a metallic piece into concrete during the concreting process and measure the force to remove it through a dynamometer.

In the 60’s, a technique was developed in the United States to correlate the resistance of concrete and pin, or screw penetration depth when shot by a pistol against a concrete surface (Gonçalves, 1986).

The “Windsor Probe” method was used by Arni at around 1964 and its purpose was to evaluate the resistance of concrete by means of steel pin penetration. The method consisted in the use of a steel pin gun that impels the pin into concrete by means of a gunpowder charge and a scale to measure pin penetration depth. Arni states that pin penetration reflects “exact compression resistance in a localized area”.

By the end of the 70’s, the method suffered an adaptation in Brazil with the se of a gun and pins of the WALSYWA brand. VIEIRA, (1978). Using the results obtained from the 55 mm pins drilled into the test bodies in beam and cylindrical shape, produced from 05 different concrete traces, subsequently with the creation of a table relating steel pin penetration into the test sample concrete, and the axial compression test obtained from the ruptured test samples at ages 3, 7 and 28 days.

In the 80’s, Nasser and Al-Manseer developed a pin penetration device that applies a reduced quantity of energy as against that of the Windsor drill.

This procedure for pin penetration testing was incorporated into ASTM C803 in 1983. A spring load device impels a high hardness steel pin of 3.56 mm diameter into concrete.

The depression from the pin’s impact is cleaned by an air blast and pin penetration depth measured by graduated scale (ACI 228, (1995).

ASTM C803 “Standard method for penetration resistance of hardened concrete” subsequently suffered two revisions, one in 1990, and the most recent in 2003, becoming ASTM C 803 M - 03.

In spite of introduction by Vieira of this type of test in 1978, adapting the Walsiva gun instead of the one used by the Windsor Probe method, the tests performed over the years and the scientific papers published in Brazil, there is still no standardization for the pin penetration method.

Presentation of “Non-Destructive Tests: Resistance to Crushing of Bulk Mass as Concrete Resistance Evaluation Variable”, created by Castro and Ferreira at the 15th WG in Rome, and won jubilee 200 medal of the congress in reference. The work used non-destructive pin penetration, adherence and ultrasound tests, and proved that the use of different tests does not influence concrete resistance evaluation, but the use of bulk mass significantly influenced the test results.

3. Methodology

3.1. Sclerometry Test Method

This method should not be considered as replacement to other methods but as an extra method or complementary test. Sclerometric methods provide information on the superficial hardness of concrete at about 20mm depth, in the case of operating with percussion energy sclerometers at about 2.25 N.m.

This method provides optimum hardness reading of concrete surface. The correlations with the other properties of concrete are empirically determined or verified through other specific tests. The sclerometric methods should be mainly used in the following circumstances: For concrete surface hardness verification, for comparison with concretes with referential, and to obtain estimated resistance to concrete compression.

The detailed sclerometry test procedure consists in: 1) the reflection sclerometer should be applied orthogonally to the test area. The percussion bar should be pressed against a test area spot, previously delimited, and before the bar completely disappears into the sclerometer body, the hammer should be released. 2) The release of the hammer should be made through the gradual increase of pressure on the device's body. After the impact, the indicator located on the sclerometer scale directly provides the sclerometric index. It can be locked by a pressure button to enable safer reading I areas of little luminosity, or in positions of difficult access. 3) The sclerometer should preferentially be applied in horizontal position and consequently over vertical surfaces. For application in different positions, the sclerometric index should be corrected with the coefficients provided by the sclerometer manufacturer.

Figure 1. The Sclerometer Test

3.1.2 Test Influencing Factors

The factors that can influence sclerometry tests are: Type of cement, type of aggregates, type of surface, surface humidity conditions, carbonation, age, sclerometer operation, and other factors (specific concrete mass; leanness of the tested structural element; proximity between test area and concrete fault; concrete tension conditions; sclerometer and concrete temperature; cement consumption; type of cure; surfaces calcinated by high temperatures - fire).

3.1.3. Equipment

Basically comprised of a spring-driven hammer that hits, by means of a rod and with a tip in the form of ball cap, the test area. The energy of the impact is in part used in the permanent deformation inflicted on the test area, and in part, elastically conserved, enabling, at the end of the impact, the hammer's return.

The higher the surface hardness tested, the lesser portion of energy converted into permanent deformity and consequently, the higher the hammer’s recoil or reflection. Based on the characteristics of the concrete structure and according to the higher or lesser degree of desired precision, one must choose one of the following sclerometer types: 1) with 30 N.m percussion energy, best suited for large concrete volume jobs; 2) With 2.25 percussion energy, with or without automatic recording tape, which can be used in normal building construction cases; and 3) With 0.75 N.m percussion energy, with or without automatic recorder tape, which is best suited for elements of reduced small sizes and sensitive to impact.

During the test one may also use the following accessories: Disk or prism in carborundum for manual polishing of the test area and polishing machine with wear and polish accessories for concrete surfaces.

The sclerometer should be checked before use, or on every 300 impacts, as follows: 1) With the use of a special steel anvil with a steel guide, about 16 kg mass, placed over hard base and leveled, with the surface to suffer the impact showing hardness of 5000 MPa, and providing sclerometric indexes of 80; 2) Performing at least 10 impacts over the anvil on each inspection; 3) When these checking impacts show sclerometric index of 75 on average or lesser, the sclerometer cannot be used and must be calibrated; 4) On individual sclerometric index obtained between 10 impacts should differ from the average of +-3 . When that happens, the device cannot be used and must be calibrated.

3.1.3. Test Accuracy

According to Malhota (1991), there is consensus as to the estimate of concrete resistance to compression in the tests performed on samples in lab, presenting accuracy of +/- 15 or 20%, as long as the samples have been cast, cured and tested under conditions identical to those when the correlation curves were established. In case the test is directly made into the structure, the estimate of the concrete's resistance to compression presents accuracy of about +/- 25%.

According to Facaoaru (1984), accuracy of such type of test is as follows: 1) 12 to 18% - if samples or controls are available and if the concrete's composition is known; 2) 15 to 20% - if only test samples and controls are available; 3) 18 to 20% - if only the concrete's composition is known; 4) Above 30% - when access is available to supporting data only, but meeting the condition that the concrete is aged below 1 year.

3.2. Pin Penetration Test

According to ACI 228 (1995), the penetration test technique measures penetration. Therefore, it is used to estimate concrete resistance with the use of calibration curves.

The method involves pin shots with a gun, the projective penetrates into the concrete, with the influence of the pin's initial kinetic energy and the concrete's energy absorption. The pin penetrates into concrete until its initial kinetic energy is completely absorbed by the concrete. Part of this energy is absorbed by friction between the pin and the concrete, and another part is absorbed due to the fracture suffered by the concrete from the pin. (ACI 228. (1995)).n of pin introduced into hardened concrete per unit measure.

To perform the test one only needs access to one side of the structure. It is necessary to avoid steel bars, in the case of reinforced concrete, and observe the precautions inherent to the use of firearms. After the measurements, remove the pins, leaving damage on the surface of about 75 mm in diameter (BS1881: Part 201,1986).

The equipment used in this method, which is a pin gun, is simple and durable; and not very sensitive to operator experience. The method is useful in concrete resistance monitoring, with reduced damage to structural pieces. (MALHOTRA,1984, ACI- 364,1993).

The detailed implementation of the pin penetration test procedure consists in: 1) The equipment is prepared, introducing the smooth steel pin into the gun chamber, then in a special casing, place the cartridge or pin driver. The casing should be practically together or mounted on the steel pin head in order to receive the full force of the shot; 2) with the gun ready, take it to the concrete surface to examine, the surface of which must be flat to enable penetration without hindrances; 3) Pull the trigger to drive the pin into the concrete, the depth of which will depend on the concrete's quality. Remove the gun for reloading, and measure the part of the pin sticking out of the concrete surface, subtract the measure from 55mm of total pin length, which gives penetration value; 4) Each penetration in mm corresponds to a rupture tension of the concrete to compression, according to correlation table obtained; 5)Perform at least 5 penetrations for each test in an area of 30 cm X 30 cm.

Figure 2. Pin Penetration Test

3.2.1. Test Influencing Factors

According to BS 1881: Part 201, 1986, the method is mainly influenced by the type of aggregate, not being sensitive to factors such as moisture level, cement type and sure. According to ACI 228 1R (1995), resistance of mortar as well as of aggregates influences pin penetration depth, while in the compression resistance test the mortar has a predominant influence in the result.

According to BS 1881: Part 207 (1992), the correlation between penetration resistance and compression resistance is influenced by the characteristics and proportionally, of the large and small aggregates in the concrete.

Due to the pin's penetration into concrete, the results of this test are not influenced by the texture and humidity of the surface, but the finishing with mason spatula provides a harder surface, which may lead to reduced penetration values as well as higher dispersion of the results (ACI 228 1R-89, 1988).

The result of this test can be influenced by the type of mould used, whether wood or steel (ASTM C803, 1990).

Bungey (1989) mentions in general that equipment manufacturers only consider in this test the hardness of the aggregate in the proposed calibration curves, but there is also influence of aggregate adherence due to its surface characteristics.

In relation to humidity conditions, maximum dimension (above 50mm), and aggregate level, Bungey reports that these influences are not as significant as aggregate hardness and type.

Yun et al (1988) investigated compositions with aggregates Dmax.=25mm and Dmax.=40mm, and verified that the correlation of this test with the compression resistance is influenced by the dimension of the large aggregate.

Ferreira (1999) analyzed the effect of resistance to large aggregate crushing as second independent variable in regression graphics, in the case of pin penetration test and concrete compression resistance. Analysis of the variance of pin penetration test results in concrete attested that the resistance to aggregate crushing significantly influenced pin penetration test results.

3.2.2. Equipment

The gun used in the Windsor Probe is internationally renowned for use in pin penetration tests, recommended by ASTM C803 and BS 1881. It has several shapes and accessories that can be used not only for concrete, but also used for tests on mortar or wood.

The Windsor Probe AT 238/S system is recommended for tests on blocks, mortar joints, concrete, pre-cast slabs or ducts, and can be used for pin penetration tests to measure compression resistance of up to 5300 psi (36.9 MPa). The pin can be reused up to seven times because of the special steel from which it is made.

The Windsor HP Probe recommended by ASTM C803 and BS 1881 can be used for pin penetration tests to measure concrete compression resistance above 17000 psi (117 Mpa), providing excellent correlation with destructive test results – variance of 1% to 5%.

The gun comes with an LCD that allows the use of the instructions manual during the test and the transfer of results to a computer. The accessories for the equipment are the steel pins, pin driving fuse, and the depth meter. The electronic measuring device is programmed for parameter selection such as aggregate hardness, specific concrete weight and standard measurement unit.

In Brazil, the equipment used is the powder pin-driver gin with the accessories of the Walsiva brand, introduced by Vieira (1978) and used until today.

3.2.3. Test Accuracy

The resistance estimate presents accuracy of about +15 to +20% as long as the test samples are cast, cured and tested in conditions identical to those in which the calibration curves are established (Malhorta, 1984). According to the same author, in general, the variation coefficient of the penetration results is of 6 to 10%.

Bungey (1989) mentions that it is impossible to estimate resistance in the reliability interval of 95% with +20% accuracy, for a combination of three penetrations. Upon investigating the variances inherent to the penetration test, Yun et AL (1988) obtained coefficient means varying from 11.7%, 16.1% and 15.4% for tests in mortar, in concrete with aggregate Dmax.=25mm, and in concrete with aggregate Dmax=40, respectively.

Turkstra et al (1988) presented variation coefficients for this Test of about 12.4% to 15.8%. Ferreira (1999) verified that of five correlations obtained for the pin penetration test with short 22 load, two equations were rejected and that of the correlations with long load pin penetration tests, the five were rejected, concluding that load 22 long is excessive and that result is influenced more by the large aggregate.

ASTM C803 (1990) mentions that for a given concrete a given test equipment, the relation between compression resistance and penetration resistance can be established experimentally.

The correlation may change according to the type of cure, aggregate type and size, and resistance level developed in the concrete. The correlations can be with the resistance obtained in controls extracted from the structure as well as from cast samples.

ACI 228.1R (1989) recommends that for tests in 6 different ages, one must have a combination of 12 cylindrical samples and one slab with dimensions that allow for 18 penetration tests. For each age, test 2 cylinders and perform 3 penetrations. For vertical element tests in situ, correlation should be established by means of cast walls, where penetration test is made, and on the side, control extractions.

According to Bungey (1989), three measurements are needed in order to obtain the mean with the same degree of reliability of the compression resistance test where 02 cylindrical samples are tested. As agreed in ACI 228.1R-89 and BS 1881: Part 207 (1992).

4. Results

This job compared the resistances obtained in concrete compression tests performed in lab presses and the results from the non-destructive sclerometry and pin penetration tests.

There is a similar job (Dissertation: “Correlation Curves to Characterize Concrete Used in Rio de Janeiro by Means of Non-Destructive Tests", Rio de Janeiro, COPPE/UFRJ, M.Sc., Civil Engineering, 2005) in function of aggregate types and cements used in concrete. This work does not contemplate types of aggregates and/or cements.

We proposed the implementation of sclerometric and pin penetration tests, and the reliability analysis thereof with the purpose of studying the results of the tests for concrete compression verification by means of analysis and comparison of several data collected in lab through concrete compression tests, as demonstrated in the tables presented below.

4.1. Table of Results for Concrete with Fck 20MPa, Fck 25MPa, Fck 30MPa

Table 1. Fck 20MPa

DOSAGE		FcK –MPa	CP 1 – Mpa		CP 2 – MPa	Mean
		20	23.3		24.6	23.95
* ↓	**SCLEROMETRY – AVERAGE PER TEST**					
	22.1	21.5	19.1	23.7	20.4	22.3
→	22.3	19.4	20.7	24.1	21.8	22.9
PIN PENETRATION – MEAN PER TEST						
20.8	24.2	21.7	22.3		20.1	23.6

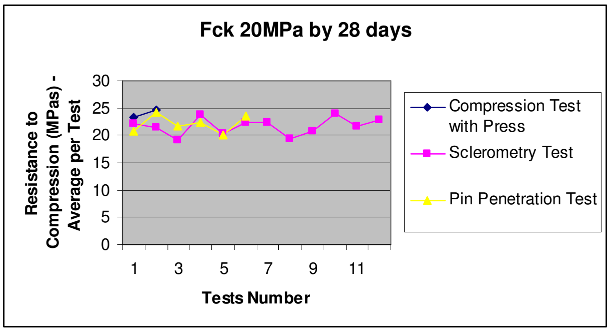

Figure 3. Chart Fck 20Mpa by 28 days

Table 2. Fck 25MPa

DOSAGE (2)		FcK –MPa	CP 1 – Mpa		CP 2 – MPa	Mean
		25	27.2		28.3	27.7
* ↓	**SCLEROMETRY – AVERAGE PER TEST**					
	26.1	28.4	25.7	27.1	26.4	25.2
→	28.1	24.7	26.3	22.5	25.1	24.6
PIN PENETRATION – MEAN PER TEST						
27.1	23.6	25.5	26.4		23.3	25.1

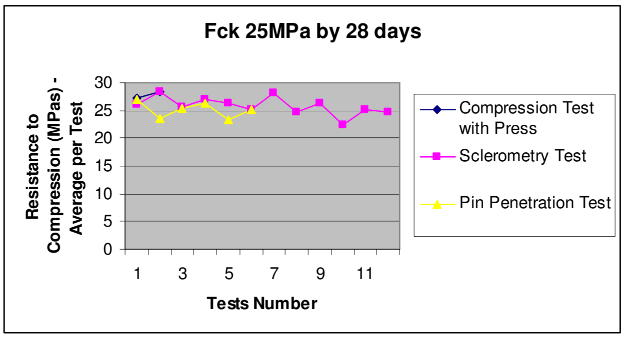

Figure 4. Chart Fck 25Mpa by 28 days

Table 3. Fck 30MPa

	FcK –MPa	CP 1 – Mpa	CP 2 – MPa	Mean		
DOSAGE (3)	30	36.4	36.1	36.2		
	SCLEROMETRY – AVERAGE PER TEST					
* ↓	28.2	33.5	31.4	29.8	32.7	28.4
→	29.4	31.5	33.1	30.2	31.9	30.7
PIN PENETRATION – MEAN PER TEST						
29.1	33.4	30.2	31.3	34.1	29.7	

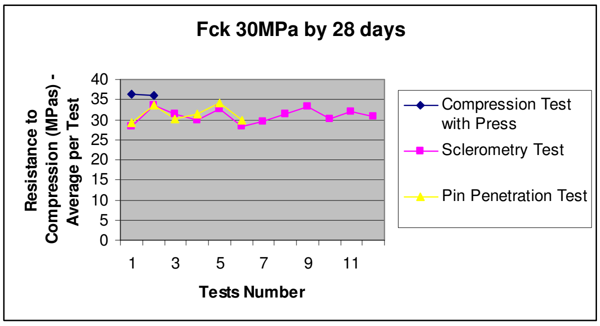

Figure 5. Chart Fck 30Mpa by 28 days

* Sclerometer Application Direction.

4.2. Table of Results for Concrete with Fck 40MPa, Fck 50MPa, Fck 60MPa, with microsilica additive

Table 4. Fck 40MPA with Microsilica

	FcK –MPa	CP 1 – Mpa	CP 2 – MPa	Mean		
DOSAGE (4)	40	43.7	42.4	43.0		
	SCLEROMETRY – AVERAGE PER TEST					
* ↓	41.1	42.3	43.5	39.7	41.3	44.1
→	40.3	42.7	39.4	41.2	43.1	40.1
PIN PENETRATION – MEAN PER TEST						
40.4	43.3	38.9	44.1	39.9	41.5	

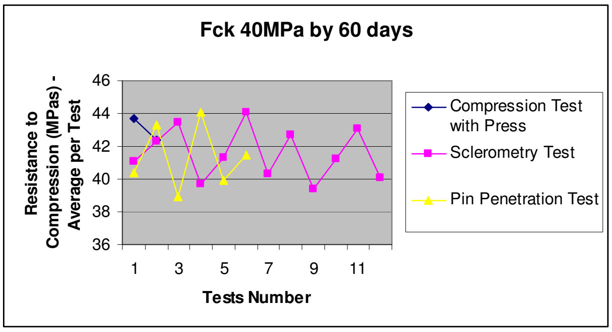

Figure 6. Chart Fck 40Mpa by 60 days

Table 5. Fck 50MPA with Microsilica

	FcK –MPa	CP 1 – Mpa	CP 2 – MPa	Mean		
DOSAGE (5)	50	57.7	54.9	56.3		
	SCLEROMETRY – AVERAGE PER TEST					
* ↓	50.1	52.9	49.8	50.4	53.1	51.9
→	51.6	48.7	53.6	52.3	52.8	54.2
PIN PENETRATION – MEAN PER TEST						

53.2	54.6	50.1	49.6	53.7	51.2

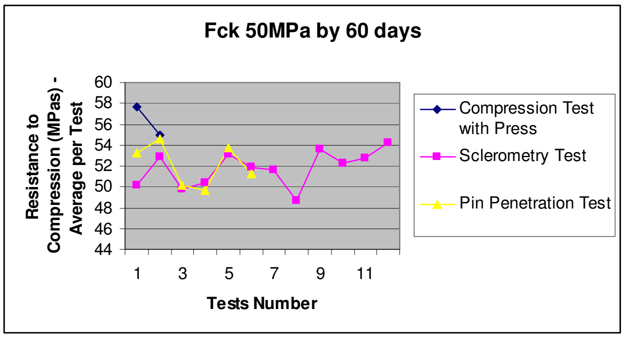

Figure 7. Chart Fck 50Mpa by 60 days

Table 6 - Fck 60MPA with Microsilica

DOSAGE (6)		FcK –MPa	CP 1 – Mpa	CP 2 – MPa	Mean	
		60	64.8	62.7	63.7	
*	**SCLEROMETRY – AVERAGE PER TEST**					
↓	61.4	63.1	59.8	58.7	61.5	64.3
→	63.6	58.9	60.1	62.4	60.7	64.1
PIN PENETRATION – MEAN PER TEST						
63.1	59.8	64.3	60.5	61.1	62.4	

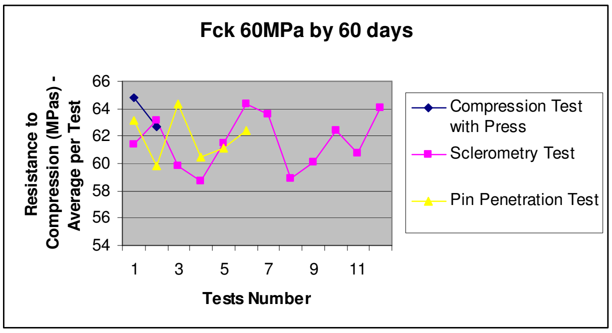

Figure 8. Chart Fck 60Mpa by 60 days

* Sclerometer Application Direction.

5. Conclusion

We wish to prove, through reliability studies in statistics that the sclerometry and pin penetration tests enable effective reliability of concrete compression resistance, establishing more precise correlation between sclerometry and pin penetration results with those from sample resistance tests, as the latter are deemed to me more reliable and consequently the most often used in the market today.

We were able to verify and analyze the information from the different conditions to which the concrete was submitted during the ´proposed tests, evaluating the variances and considering the reliability differentials, showing the reliability of the sclerometry tests and pin penetration, as long as the conditions essential to performing the tests are in place.

6. Bibliographical references

American Society for Testing and Materials, ASTM C 803/C 803M International, 2008 “Standard Test Method for Penetration Resistance of Hardened Concrete”, United States.

Bauer, L.A.F, “Materiais de Construção - Volumes I e II”, 1994, São Paulo.

Comitê Brasileiro de Cimento, Concreto e Agregados, 1985, “NBR 7584/ 1995”, Rio de Janeiro, ABNT.

Coutinho, A. S., “Fabrico e Propriedades em Betão”, 1974, LENEC, Lisboa.

Evangelista, A. C. J., 2002, “*Avaliação da Resistência do Concreto Usando Diferentes Ensaios Não Destrutivos”,* Tese de Doutorado, COPPE / UFRJ, Rio de Janeiro, RJ, Brasil.

Facaoru, I., 1984, “Romanian Achievements in Nondestructive Strength Testing of Concrete”, *In Situ / Nondestructive Testing of Concrete*, Special Publication SP – 82, American Concrete Institute, Detroit, pp.35–56.

Lafraia, J. R. B., 2000, “Manual de Confiabilidade, Mantenabilidade e Disponibilidade”, Rio de Janeiro: Qualitymark.

Lewis, E. E., 1996, “Introduction to reliability engineering”, New York: John Wiley.

Machado, M.D., 2005, “Dissertação: Curvas de Correlação para Caracterizar Concretos Usados no Rio de Janeiro por meio de Ensaios Não Destrutivos.”, Tese de Doutorado, COPPE/UFRJ, Rio de Janeiro, RJ, Brasil.

Soong, T. T., 1986, “Modelos Probabilísticos em Engenharia e Ciências”, Rio de Janeiro: Livros Técnicos e Científicos.

Vieira, D. P., 1978, “Método Brasileiro de Penetração de Pinos”, *XIX Jornadas Sulamericanas de Engenharia Estrutural*, Santiago, Chile.