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Títol

Comparison of destructive and nondestructive methods of material properties testing with focus to historical building materials – masonry (ceramics and stone), mortars and plasters

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ABSTRACT

Title *Comparison of destructive and nondestructive methods of material properties testing with focus to historical building materials – masonry (ceramics and stone), mortars and plasters*

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The present document is about the realization of nondestructive test and destructive test with different types of materials and the comparison of the obtained results for both methods.

The nondestructive methods (NDT) are characterized for not to change permanently the physical, chemical, mechanical or dimensional properties of the materials, that is involving a zero or negligible damage. Different methods of nondestructive testing are based on the application of physical phenomena such as electromagnetic waves, elastic emission of subatomic particles, capillary absorption and any evidence that does not involve damage to the sample examined.

The aim of NDT is to detect discontinuities in materials without destroying them, determine the location, orientation, size and type of discontinuities and establish the quality of the material, based on the study results and the severity of the defects. The main disadvantage is that in general, the NDT provide less accurate data variable that destructive measuring method (DT).

The aim of DT is to determine the value of certain material properties such as mechanical strength, toughness or hardness. The execution of destructive tests involve the destruction of the material, so the DT can be considered as direct physical methods that change permanently the physical, chemical, mechanical and dimensional properties of the subject analyzed. The main disadvantage is that these tests cannot be applied to all components of the building to check if the material characteristics fulfills the specified during design, because that would be destroyed and would lose their utility

In order to reach a direct relation between the parameters obtained by nondestructive testing those obtained with the parameter obtained with destructive methods, an experimental campaign, that is part of a long-term project, was made.

This thesis presents the works of the author about the preparation and realization of the different test done in this course and of the comparative study of the obtained results, along with a study of the nondestructive test and a summary of how to obtain resistance parameters of materials using destructive test.

RESUMEN

***Titulo** Comparación de ensayos destructivos y no destructivos de propiedades de materiales con especial atención a materiales usados en edificios históricos– mampostería (cerámicas y piedras), morteros y yesos.*

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El presente documento trata de la realización de ensayos no destructivos y de ensayos destructivos sobre diferentes tipos de materiales y de la comparación de los resultados obtenidos por ambos métodos.

Los ensayos no destructivos (END) se caracterizan por no alterar de forma permanente las propiedades físicas, químicas, mecánicas o dimensionales de los materiales, es decir que implican un daño imperceptible o nulo. Los diferentes métodos de ensayos no destructivos se basan en la aplicación de fenómenos físicos tales como ondas electromagnéticas, elásticas, emisión de partículas subatómicas, capilaridad, absorción y cualquier tipo de prueba que no implique un daño a la muestra examinada.

Los END tienen como objetivo detectar discontinuidades en materiales sin destrucción de los mismos, determinar la ubicación, orientación, tamaño y tipo de discontinuidades y establecer la calidad del material, basándose en el estudio de los resultados y en la severidad de los defectos. La principal desventaja es, que en general, los END proporcionan datos menos precisa de la variable a medir que los métodos destructivos (ED).

En referencia a los ED, cabe decir que tienen como objetivo principal determinar el valor de ciertas propiedades de los materiales como la resistencia mecánica, la tenacidad o la dureza. La ejecución de las pruebas destructivas involucra la destrucción del material, por lo que los ED se pueden considerar como métodos físicos directos que alteran de forma permanente las propiedades físicas, químicas, mecánicas o dimensionales del sujeto analizado. La principal desventaja es que estas pruebas para la comprobación de si las características del material cumplen con lo especificado durante el diseño, no se pueden aplicar a todos los componentes del edificio, debido a que serían destruidos y perderían su utilidad.

Con la intención de llegar a una relación directa entre los parámetros obtenidos con ensayos no destructivos y con los obtenidos con ensayos destructivos, se realizó una campaña experimental que es parte de un proyecto a largo plazo.

En esta tesina se presentan los trabajos realizados por el autor de preparación y realización de los diferentes ensayos realizados sobre el curso y del estudio comparativo de los resultados obtenidos, junto con un estudio de los diferentes ensayos no destructivos existentes en la actualidad y un resumen de la obtención de parámetros relacionados con la resistencia de materiales mediante ensayos destructivos.

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1 INTRODUCTION

1.1 General information

This thesis is based on the comparison of nondestructive methods and destructive methods of material properties testing with focus to historical building materials – masonry (ceramics and stone), mortars and plasters.

The nondestructive methods will include rebound tests and ultrasonic measurements. Destructive methods will include test on drill cores and specifically fabricated test specimens. These tests are realized in the Experimental Center laboratory located in the building D of the faculty of Civil Engineering in the Czech Technical University in Prague.

With this study it would be possible to obtain relations of the parameters obtained with the non destructive methods with the parameters obtained with the destructive methods. These relations are obtained for each type of material tested.

1.2 Non destructive methods

Nondestructive testing (NDT) is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system. In other words, when the inspection or test is completed the part can still be used.

In contrast to NDT, other tests are destructive in nature and are therefore done on a limited number of samples, rather than on the materials, components or assemblies actually being put into service. These destructive tests are often used to determine the physical properties of materials such as impact resistance, ductility, yield and ultimate tensile strength, fracture toughness and fatigue strength, but discontinuities and differences in material characteristics are more effectively found by NDT.

Today modern nondestructive tests are used in manufacturing, fabrication and in-service inspections to ensure product integrity and reliability, to control manufacturing processes, lower production costs and to maintain a uniform quality level. During construction, NDT are used to ensure the quality of materials and joining processes during the fabrication and erection phases, and in-service NDT inspections are used to ensure that the products in use continue to have the integrity necessary to ensure their usefulness and the safety of the public.

1.3 Destructive methods

Destructive testing (DT) includes methods where your material is broken down in order to determine mechanical properties, such as strength, toughness and hardness.

These properties can't be examined with nondestructive methods, as specimens of the material must be extracted. Destructive testing is generally most suitable and economic for mass produced objects, as the cost of destroying a small number of pieces is negligible. The samples are put under different loads and stress. That way we can analyze in which point your material eventually gives up and cracks. The results gained are then compared to regulations and/or quality guidelines.

Destructive tests are best when used together with nondestructive methods: this combination gives the best information on materials and welds. Nondestructive tests show if cracks, corrosion or other faults exist. Destructive tests in turn indicate how and when the objects are in danger of breaking down or failing.

Some of the benefits of destructive testing are the verification of the properties of a material, the determination of the quality of welds, reduction of failures, accidents and costs and ensure compliance with regulation.

1.4 Objective

In general, the NDT provides less accurate data about the measured variable than the DT. Despite of it, sometimes it is not possible to use them (when the material can't be destroyed) and is when the NDT are useful. This is more visible in historical buildings.

So, the main objective of this thesis is to compare the NDT with the DT in order to obtain a correlation between the parameters that can be obtained with both techniques. The idea is that knowing some correlation, it would be possible to evaluate in a proper way properties like resistance, durability or strength of a historical building without the needed of doing destructive tests. And, moreover, it would be helpful to rely more in the results obtained with NDT when there is the needed of evaluating the condition of a building and to do the required corrective actions only with the NDT data.

1.5 Contents

In the first chapter of this thesis is given a brief introduction about why it has been done and what topics are covered in it.

In the second chapter it is explained the non destructive methods in a general way and then an explanation method by method. The most interesting methods for this thesis are explained deeper, for the others are only given a short description. Finally is presented a table where all the NDT are summarized.

In the third chapter it is explained the destructive methods in a general way and then it is explained those test that provide interesting parameter for this thesis, which are: the compressive strength, the tensile strength and the Young’s modulus.

In the fourth chapter are detailed the works and procedures done during this academic course such as the non destructive test and the destructive test of the materials.

In the fifth and last chapter is done a brief general conclusion of this thesis and about the work developed through the academic year. Moreover, it is made an assessment about the work that, from the point of view of the author of this thesis, it should realize during the next academic year.

2 NONDESTRUCTIVE METHODS

2.1 Introduction to nondestructive methods

The nondestructive testing (NDT) methods are a wide group of analysis techniques used to evaluate the physical, chemical, mechanical or dimensional properties of a material. These tests produce an imperceptible or null damage to the material, meaning that without interfering in any way with the integrity or its suitability for service the material can be evaluated. Because of this NDT provides an excellent balance between quality control and cost-effectiveness.

The application of NDT methods to the solution of civil engineering problems has sometimes been disappointing. This has arisen because, in general, the nondestructive methods provide less accurate data about the variable to measure than the destructive or because of the method is inappropriate to the problem under consideration. In some cases, these problems could have been avoided by taking expert advice before initiating the survey. Nevertheless they are often cheaper because of it doesn't imply the destruction of the sample.

It is often advisable to undertake a feasibility study on the structure to assess the suitability of the proposed NDT techniques for the investigation of the structural problem. An example of a procedure is given below:

- Phase 1	Visual inspection.
- Phase 2	Analysis of load carrying capacity.
- Phase 3	Review need for further investigation - if none, then revert to visual inspection schedule. If further investigation required, then proceed to Phase 4.
- Phase 4	Before undertaking any more detailed field study, research needs to be undertaken of the origins: who designed and built it and the possible style of construction.
- Phase 5	Cost effectively chooses the most suitable strategy for further investigation. An NDT method may be chosen for one of two reasons: (a) when a direct physical measurement strategy was inadequate or too expensive; and (b) when there is a need to extend a limited physical investigation.
- Phase 6	Implement the investigation technique.

Advantages of the NDT

The NDT can be used in every step of a productive process, as for example:

- During the reception of raw materials arriving at the warehouse: to check the homogeneity, the chemical composition and evaluate some mechanical properties.

- During the different steps of the fabrication process: to check if the component is free of defects.

- In the final inspection: to ensure that the piece fulfill the acceptance requirements.

- In the inspection and the checking of the parts and components in service: to verify that they can still be used safely or to know the remaining life time.

Due to there is no alteration of the material properties and for this reason there is no wastes, with the NDT only there are loses when deficient pieces are detected.

Limitations of the NDT

The first limitation is that in some occasions the initial investments of these type of test are high, but can be justified if it is rightly analyzed the cost-benefit relation.

Another limitation is that the physical property to control is measured in an indirect way, moreover is evaluated qualitatively or by comparison. This limitation can be overcome if there are appropriate comparative or referral patterns that allow a good calibration of the inspection systems.

When there aren’t inspections procedures properly prepared or when there aren’t appropriate comparative or referral patterns, a same indication can be evaluated in a different way by different inspectors.

Although the NDT are relatively easy to apply, the personal that make them have to fulfill some requirements: they have to be properly trained and qualified and they have to have the necessary experience due to get a correct interpretation and evaluation of the results and due to avoid material waste or time waste.

Benefits of using NDT

A combination of NDT with a statistical analysis contributes to improve the manufacturing process control of a component and to improve the productivity of a plant.

When the NDT are used as a part of a prevention inspection it reduces significantly the repair costs, in the direction of saving time and resources with the reparation.

A combination of NDT with other activities of the quality control helps to ensure and maintain a uniform level of quality of the final product.

Another benefit is that using the NDT as an auxiliary tool of the industrial maintenance, there is a better evaluation of the components in service, so it allows optimizing the corrective maintenance planning.

NDT techniques

There are many NDT techniques, each based on different theoretical principles, and producing as a result different sets of information regarding the physical properties of the structure. These properties, such as compression and shear wave velocities, electrical resistivity and so on, have to be interpreted in terms of the fabric of the structure and its engineering properties. Inevitably, this interpretation involves some degree of assumption about the structure, and the use of calibration measurements is an essential feature of most nondestructive surveys. Furthermore, many structural problems will be best studied by a particular NDT method, depending upon which physical properties of the construction materials offer the best chance of being reliably determined.

In general there are two classes of nondestructive test methods for concrete and masonry. The first class consists of those methods that are used to estimate strength of the material: the surface hardness, penetration resistance, pullout, break-off, pull-off, and maturity techniques belong to this category. Some of these methods are not truly nondestructive because they cause some surface damage, which is, however, minor compared with that produced by drilling a core. The second class includes those methods that measure other characteristics of the material such as moisture content, density, thickness, resistivity, and permeability. Also included in the second class are such methods as stress wave propagation, ground probing radar, and infrared thermography techniques, which are used to locate delaminations, voids, and cracks. In addition, there are methods to provide information on steel reinforcement such as bar location, bar size, and whether the bars are corroding.

There is a wide range of NDT methods, which are used in the civil engineering industry. Some of the nondestructive methods are described, emphasizing in those most important and those that are used in the research, in the following subchapters.

2.2 Ultrasonic methods: pulse velocity method

This method can be used for detecting internal cracking and other defects as well as changes in the material such as deterioration due to aggressive chemical environment and freezing and thawing. One of the ultrasonic methods more used is the pulse velocity method. By using the pulse velocity method it is also possible to estimate the strength of test specimens and in-place concrete.

The pulse velocity method is a truly nondestructive and noninvasive method, as the technique uses mechanical waves resulting in no damage to the material element being tested. A test specimen can be tested again and again at the same location, which is useful for monitoring concrete undergoing internal structural changes over a long period of time.

Figure 2.1 Pulse velocity instrument (James Instruments, Inc.)

The test instrument (Figure 2.1) consists of a means of producing and introducing a wave pulse into the material (pulse generator and transmitter) and a means of sensing the arrival of the pulse (receiver) and accurately measuring the time taken by the pulse to travel through the material.

Figure 2.2 illustrates different ways of the ultrasonic transmission:

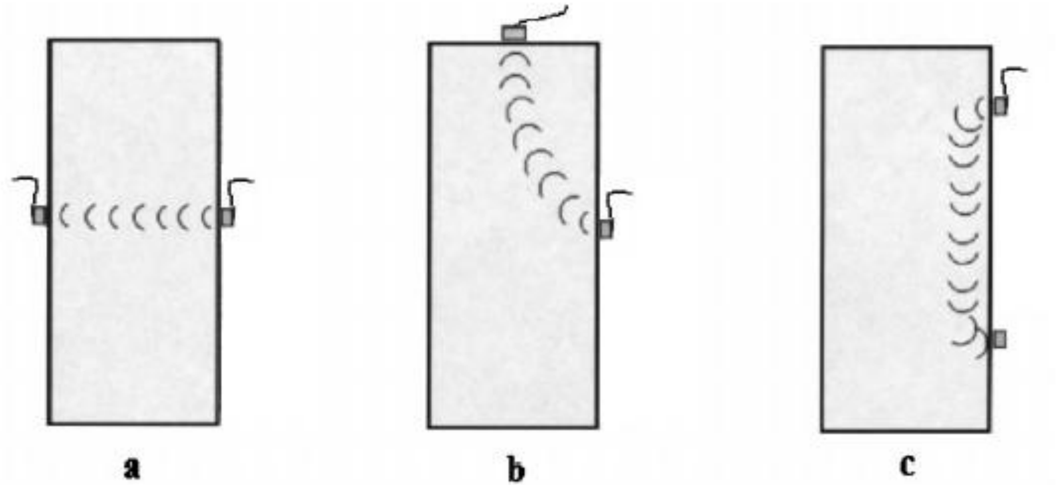

Figure 2.2 Transmission modes for ultrasonic tests: (a) direct; (b) semidirect; (c) indirect.

This form of testing is used successfully at ultrasonic frequencies for the detection of flaws in metal castings and is the first nondestructive technique that was developed for the testing of concrete. However, it is much less practical in concrete and masonry, which have much higher attenuation characteristics and hence lower frequency signals are required to obtain a reasonable penetration. In addition, the numerous material boundaries in these materials result in scattering of both incident and reflected waves. Despite this fact, it has been successfully used for identifying and locating specific flaws in concrete and is also applicable to the investigation of small defects within masonry walls.

The pulse velocity method has been applied successfully in the laboratory as well as in the field. Furthermore, it can be used for quality control, as well as for the analysis of deterioration.

The pulse velocity method may provide a means of estimating the strength of both in situ and precast concrete although there is no physical relation between the strength and velocity. The strength can be estimated from the pulse velocity by a pre-established graphical correlation between the two parameters.

The pulse velocity method is suitable for the study of homogeneity of concrete, and, therefore, for relative assessment of quality of concrete. Heterogeneity is defined as interior cracking, deterioration, honeycombing, and variations in mixture proportions. Heterogeneities in a concrete member will cause variations in the pulse velocity.

Although it is relatively easy to conduct a pulse velocity test, it is important that the test be conducted such that the pulse velocity readings are reproducible and that they are affected only by the properties of the concrete under test rather than by other factors. The factors affecting the pulse velocity can be divided into two categories: Factors resulting directly from concrete properties and other factors. Examples:

- Cement type: As the degree of hydration increases, the modulus of elasticity will increase and the pulse velocity will also increase

- Water-cement ratio: Kaplan, M.F. studied the effect of water/cement (*w/c*) ratio on the pulse velocity. He has shown that as the *w/c* increases, the compressive and flexural strengths and the corresponding pulse velocity

- Age of concrete: The effect of age of concrete on the pulse velocity is similar to the effect on the strength development of concrete. Jones, R. reported the relationship between the pulse velocity and age. He showed that velocity increases very rapidly initially but soon flattens

- Temperature: Temperature variations between 5 and 30ºC have been found to have an insignificant effect on the pulse velocity (Jones, R. and Facaoaru, I.). For temperatures beyond this range, the British Standards Institution recommends some corrections.

- Level of stress: Pulse velocity is generally not affected by the level of stress in the element under test. However, when the concrete is subjected to a very high level of static or repeated stress, say, 65% of the ultimate strength or greater, microcracks develop within the concrete, which will reduce the pulse velocity considerably (Popovics, S. and Popovics, J.S., and Wu, T.T and Lin, T.F.)

2.3 Rebound methods

The rebound methods or surface hardness methods for nondestructive testing are based on the rebound principle. The increase in the hardness of concrete with age and strength has led to the development of test methods to measure this property. These methods consist of measuring the rebound of a spring driven hammer mass after its impact with concrete.

2.3.1 Rebound Hammer by Schmidt

In 1948 Schmidt, E. developed a test hammer for measuring the hardness of concrete by the rebound principle. The Schmidt rebound hammer is principally a surface hardness tester with little apparent theoretical relationship between the strength of concrete and the rebound number of the hammer. However, within limits, empirical correlations have been established between strength properties and the rebound number.

The Schmidt rebound hammer is shown in Figure 2.3. The hammer weighs about 1.8 kg and is suitable for use both in a laboratory and in the field.

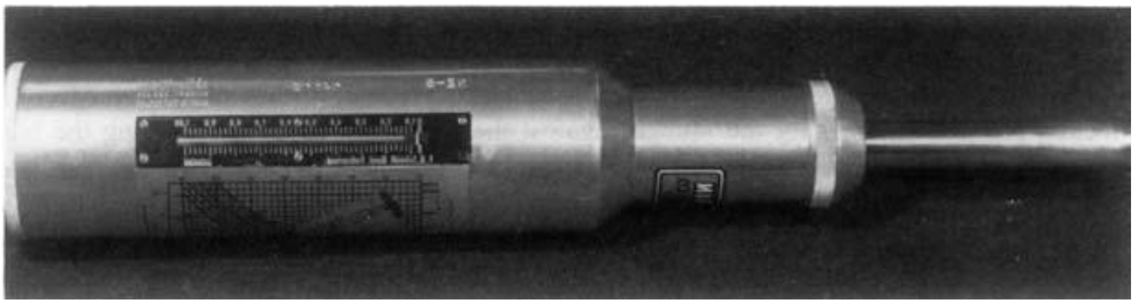

Figure 2.3 Schmidt rebound hammer

A schematic cutaway view of the rebound hammer is shown in Figure 2.4. The main components include the outer body, the plunger, the hammer mass, and the main spring. The rebound distance is measured on an arbitrary scale marked from 10 to 100. The rebound distance is recorded as a “rebound number” corresponding to the position of the rider on the scale.

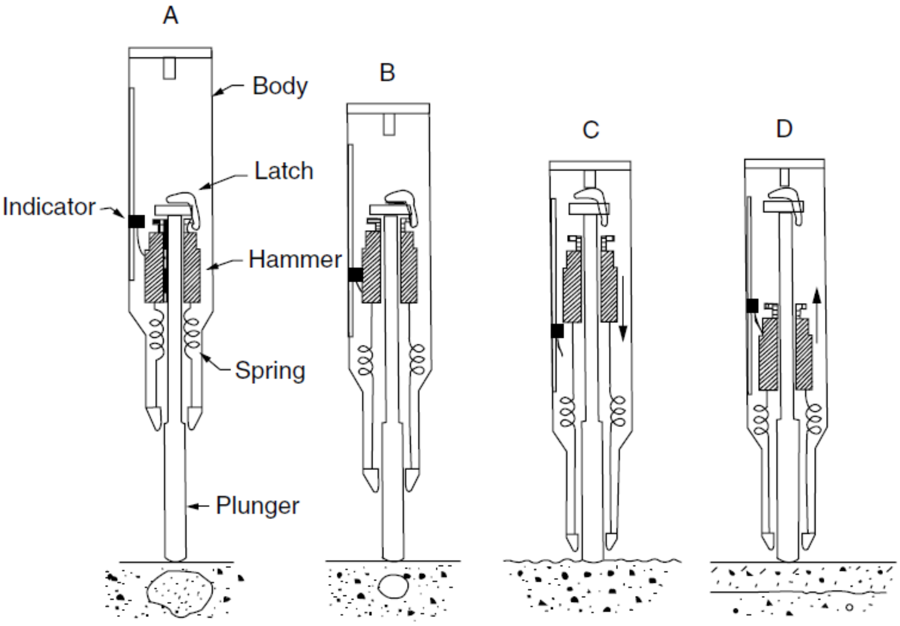

Figure 2.4 A cutaway schematic view of the Schmidt rebound hammer.

Although the rebound hammer provides a quick, inexpensive means of checking the uniformity of the material, it has serious limitations and these must be recognized. The results of the Schmidt rebound hammer are affected by:

- Smoothness of test surface: The tougher is the surface, the more accurate are the results (Kolek, J and Greene, G.W.)

- Size, shape, and rigidity of the specimens: If the section of test specimen is small, any movement under the impact will lower the rebound readings. In such cases the member has to be rigidly held or backed up by a heavy mass (Mitchell, L.J. and Hoagland, G.G.).

- Age of test specimens: It has been confirmed by Zoldners, N.G and Victor, D.J. that for equal strength, higher rebound values are obtained on 7-day-old concrete than on 28-day-old concrete.

- Surface and internal moisture conditions of the concrete: The degree of saturation of the concrete and the presence of surface moisture has a decisive effect on the evaluation of test hammer results. Zoldners, N.G has demonstrated that well-cured, air-dried specimens, when Soaked in water and tested in the saturated surface-dried condition, show rebound readings 5 points lower than when tested dry.

- Type of coarse aggregate: It is generally agreed that the rebound number is affected by the type of aggregate used. According to Klieger, P. et al., for equal compressive strengths, concretes made with crushed limestone coarse aggregate show rebound numbers approximately 7 points lower than those for concretes made with gravel coarse aggregate, representing approximately 7 MPa difference in compressive strength.

- Type of cement: According to Kolek, J., the type of cement significantly affects the rebound number readings.

- Carbonation of the concrete surface: The rebound numbers can be up to 50% higher than those obtained on an uncarbonated concrete surface

2.4 Penetration resistance methods

Penetration resistance methods are based on the determination of the depth of penetration of probes (steel rods or pins) into a material. This provides a measure of the hardness or penetration resistance of the material that can be related to its strength.

The measurement of concrete hardness by probing techniques was reported by Voellmy, A. in 1954. Two techniques were used. In one case, a hammer known as Simbi was used to perforate concrete, and the depth of the borehole was correlated to the compressive strength of concrete cubes. In the other technique, the probing of concrete was achieved by Spit pins, and the depth of penetration of the pins was correlated with the compressive strength of concrete.

2.4.1 The Windsor probe

A device known as the Windsor probe was developed for penetration testing of concrete in the laboratory as well as in situ. The device was meant to estimate the quality and compressive strength of in situ concrete by measuring the depth of penetration of probes driven into the concrete by means of a powder-actuated driver.

The Windsor probe, like the rebound hammer, is a hardness tester, and its inventors’ claim that the penetration of the probe reflects the precise compressive strength in a localized area is not strictly true. However, the probe penetration relates to some property of the concrete below the surface, and, within limits, it has been possible to develop empirical correlations between strength properties and the penetration of the probe.

The Windsor probe consists of a powder-actuated gun or driver (Figure 2.5), hardened alloy-steel probes, loaded cartridges, a depth gauge for measuring the penetration of probes, and other related equipment.

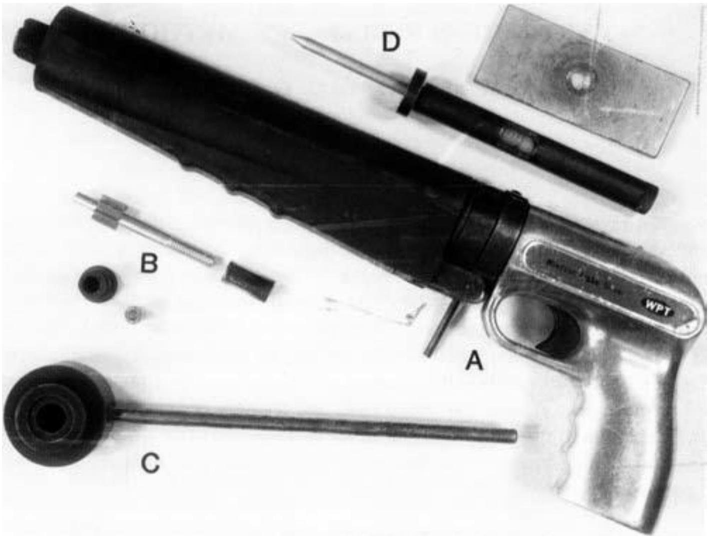

Figure 2.5 A view of the Windsor probe equipment. (A) Driver unit. (B) Probe for normal-weight concrete. (C) Single probe template. (D) Calibrated depth gauge

The probe test has limitations that must be recognized. These limitations include minimum size requirements for the member to be tested. The minimum acceptable distance from a test location to any edges of the member or between two given test locations is of the order of 150 to 200 mm; while the minimum thickness of the members is about three times the expected depth of penetration. Distance from reinforcement can also have an effect on depth of probe penetration especially when the distance is less than about 100 mm.

2.5 Pull-off test

The pull-off test is based on the concept that the tensile force required to pull a metal disk, together with a layer of concrete, from the surface to which it is attached, is related to the compressive strength of the concrete. There are two basic approaches that can be used. One is where the metal disk is attached directly to the surface and the stressed volume of material lies close to the face of the disk, and the other is where surface carbonation or skin effects are present and these can be avoided by the use of partial coring to an appropriate depth. Both these approaches are illustrated in Figure 2.6.

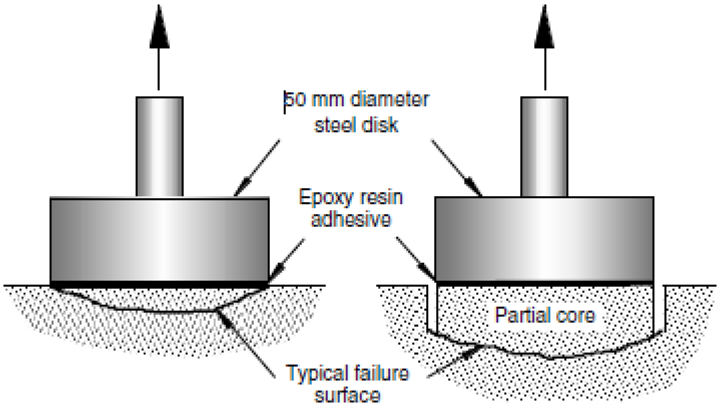

Figure 2.6 Schematic of the pull-off test showing the two procedures that can be used.

To convert the pull-off tensile strength into a cube (or cylinder) compressive strength, a previously established empirical correlation chart is used; one such typical chart is shown in Figure 2.7:

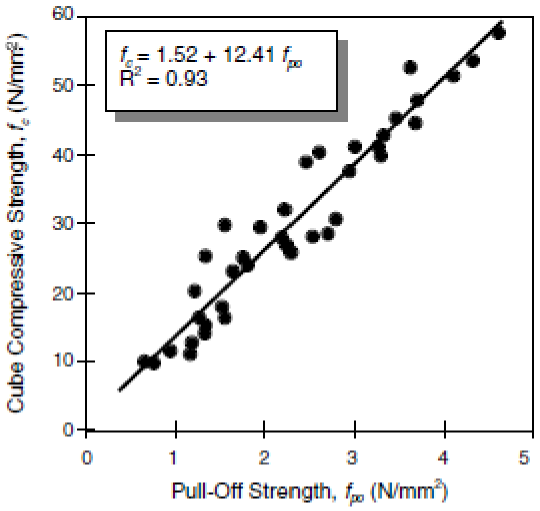

Figure 2.7 Example of compressive strength correlation for the pull-off test. (From Murray, A.McC.)

The main advantage of the pull-off test is that it is simple and quick to perform. The entire process of preparing the surface and bonding the metal disk should take no more than 15 min. Another advantage is that the damage caused to the surface after a test is not severe. The main limitation of the method is the curing time required for the adhesive. In most situations, it is normal practice to apply the disks one day and complete the test the next day. There is, however, a potential problem by doing this in that, if the surface preparation has not been completed in the correct way or if the environmental conditions are unfavorable, then this may cause the adhesive to fail. Thus, the test result is meaningless; however, this will not be discovered until after the test has been completed. To compensate for this type of problem, it is recommended that at least six disks be used to estimate the compressive strength and, if necessary, one of the individual test results can be eliminated if an adhesive failure has occurred. However, with the advances that have taken place in the development of adhesives for the construction industry, this particular limitation is becoming less of a problem.

2.6 Others methods

There are more nondestructive methods to evaluate the properties of the material, like the methods to evaluate corrosion of reinforcement or the combined methods. Following text introduces a small concept of some of them.

Visual Methods: Visual methods of surface examination, using naked eyes or with optical aid (Figure 2.8), tend to be neglected by NDT personnel but are, nevertheless, important. It is considered as the oldest and cheapest NDT method. It is also considered as one of the most important NDT method and applicable at all stages of construction or manufacturing sequence. In inspection of any engineering component, if visual inspection alone is found to be sufficient to reveal the required information necessary for decision making, then other NDT methods may no longer considered necessary.

Figure 2.8 Visual inspection of an object

Many of the most serious defects, from the strength point of view, are surface-breaking that can often be seen by careful direct visual inspection. Moreover, optical aids to visual inspection should be used whenever practicable. Industrial endoscopes, usually known as borescopes, enable internal surfaces inaccessible to the naked eye to be seen. Although considered as the simplest method of NDT, such an inspection must be carried out by personnel with an adequate preparation and experience

Impact-echo: The impact-echo is an impact method for testing of thin concrete structures developed by Sansalone and Carino. A pulse generated by impact is composed of low-frequency waves that have the ability to penetrate concrete. Sansalone an Carino used this methods to detect various types of interfaces and simulated defects in concrete slab and wall structures, including cracks and voids in plain and reinforced concrete, the depth of surface-opening cracks, voids in prestressing tendon ducts, honeycombed concrete, the thickness of slabs and overlays, and delaminations in slabs with and without asphalt concrete overlays.

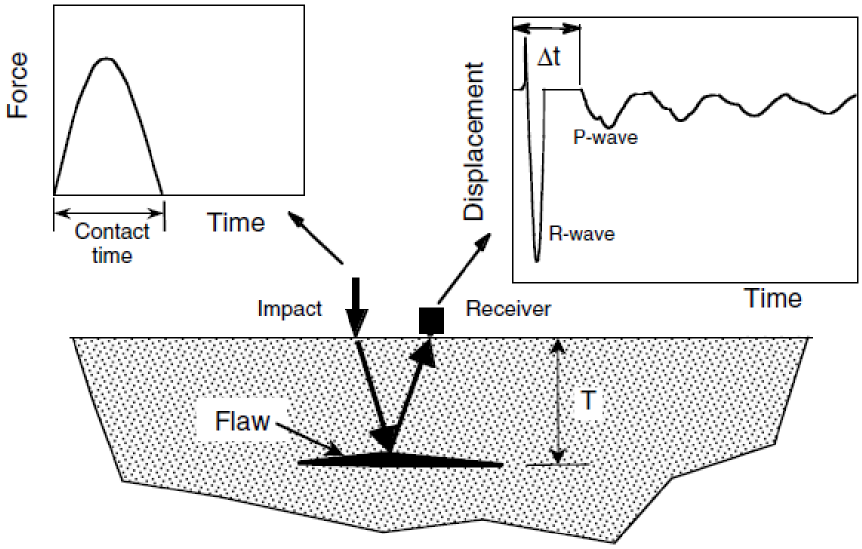

Figure 2.9 Principle of the impact-echo method

The principle of the impact-echo technique is illustrated in Figure 2.9. A stress pulse is introduced into a test object by mechanical impact on the surface. The stress pulse propagates into the object along spherical wave fronts as P- and S-waves. In addition, a surface wave (R-wave) travels along the surface away from the impact point. The P- and S- stress waves are reflected by internal interfaces or external boundaries. The arrival of these reflected waves at the surface where the impact was generated produces displacements that are measured by a receiving transducer and recorded by a data acquisition system. Because of the radiation patterns associated with P- and S-waves, if the receiver is placed close to the impact point, the waveform is dominated by the displacements caused by P-wave arrivals. The success of the method depends, in part, on using an impact of the correct duration.

An impact-echo test system is composed of three components: an impact source; a receiving transducer; and a data acquisition system with appropriate software for signal analysis and data management

The selection of the impact source is a critical aspect of a successful impact-echo test system. The force-time history of an impact may be approximated as a half-cycle sine curve, and the duration of the impact is the “contact time”. The contact time determines the frequency content of the stress pulse generated by the impact. The shorter the contact time, the higher is the range of frequencies contained in the pulse. Thus, the contact time determines the size of the defect that can be detected by impact-echo testing. As the contact time decreases and the pulse contains higher-frequency (shorter-wavelength) components, smaller defects can be detected. In addition, short-duration impacts are needed to accurately locate shallow defects. The stress pulse must have frequency components greater than the frequency corresponding to the flaw depth. As an approximation, the highest frequency component of significant amplitude in a pulse equals the inverse of the contact time.

In summary, the impact-echo method uses mechanical impact to generate a high-energy stress pulse. Surface displacements are measured near the impact point. The stress pulse undergoes multiple reflections between the test surface and the reflecting interface, and results in a periodic surface motion. This permits frequency analysis of the recorded surface displacement waveforms. The dominant frequency in the amplitude spectrum is used to determine the depth of the reflecting interface from the known wave speed. The amplitude spectra along a scan line can be used to construct a cross section of the structure, which displays the location of the reflecting interfaces. The ability of the method to detect a variety of defects has been demonstrated.

Pull-out Test: The pullout test (Figure 2.10) measures the force required to pull an embedded metal insert with an enlarged head from a concrete specimen or a structure. The pullout test is used during construction to estimate the in-place strength of concrete to help decide whether critical activities such as form removal, application of post-tensioning, or termination of cold weather protection can proceed.

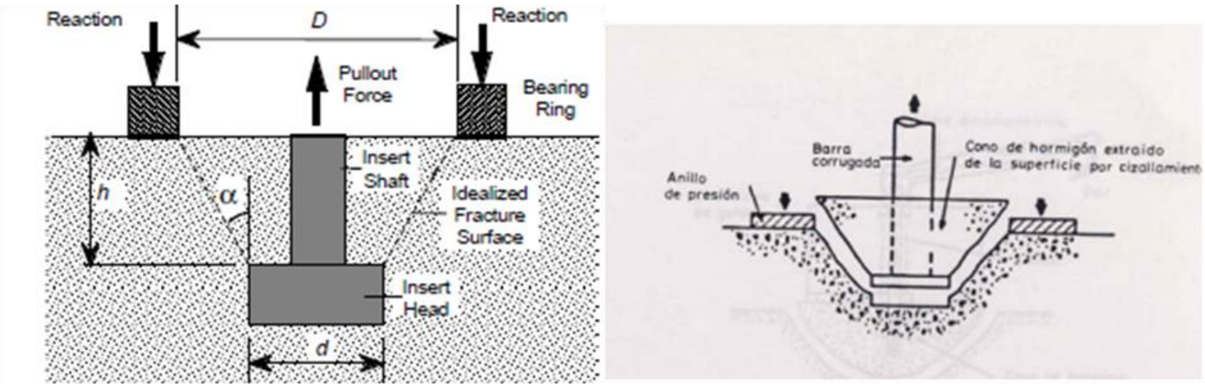

Figure 2.10 Schematic of the pull-out test.

Break-Off Test Method: In-place concrete strength is not the same as cylinder concrete strength because the in-place concrete is placed, compacted, and cured in a different manner than the cylinder specimen concrete. The Break-Off test (Figure 2.11) consists of breaking off an in-place cylindrical concrete specimen at a failure plane parallel to the finished surface of the concrete element. The BO stress at failure can then be related to the compressive or flexural strength of the concrete using a predetermined relationship that relates the concrete strength to the BO strength for a particular source of concrete. Determination of accurate in-place strength is critical in form removal and prestress or post-tension force release operation.

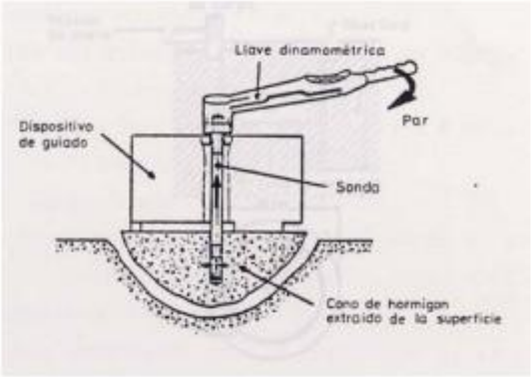

Figure 2.11 Schematic of the break-off test.

Maturity Method: The maturity method is a technique for estimating the strength gain of concrete based on the measured temperature history during curing. The combined effects of time and temperature on strength gain are quantified by means of a maturity function. Maturity functions are used to convert the actual temperature history of the concrete to a factor that is indicative of how much strength has developed.

Resonant Frequency Methods: An important dynamic property of any elastic system is the natural frequency of vibration. For a vibrating beam of given dimensions, the natural frequency of vibration is mainly related to the dynamic modulus of elasticity and density. Hence, the dynamic modulus of elasticity of a material can be determined from the measurement of the natural frequency of vibration of prismatic bars and the mathematical relationships existing between booth parameters.

Combined Methods: In order to determine the strength of *in situ* concrete more accurately, it is usual to apply more than one nondestructive method at the same time. The benefit of the small additional reliability of a combined test versus a single nondestructive test should be assessed against the additional time, cost, and complexity of combined techniques. During this research it will be used the SONREB Method: By knowing the rebound number and pulse velocity, the compressive strength is estimated (Figure 2.12).

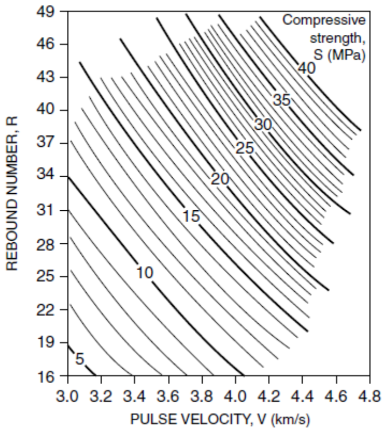

Figure 2.12 ISO-strength curves for reference concrete in SONREB method

Magnetic/Electrical Methods: Magnetic and electrical methods (Figure 2.13) are used in a number of ways to evaluate structures. These methods are used to (1) locate reinforcement and measure member thickness by inductance; (2) measure the moisture content of concrete and salt content in the masonry associated with moisture content; (3) measure the corrosion potential of reinforcement; (4) determine the thickness of a pavement or of a masonry wall; and (5) locate defects and corrosion in reinforcement by measuring magnetic flux leakage.

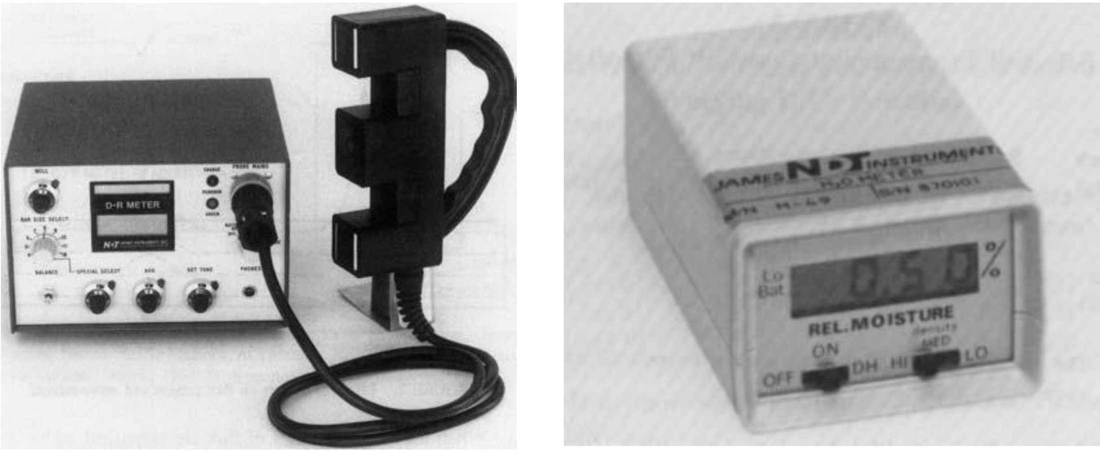

Figure 2.13 A meter used to locate reinforcement and meter designed to measure moisture content

Methods to Evaluate Corrosion of Reinforcement: A critical step in selecting the most appropriate repair strategy for a distressed concrete structure is to determine the corrosion status of reinforcing bars. The evaluation of the corrosion is a quantitative method through which the effective of the control and preventive techniques of the corrosion can be evaluated and provide the information needed to optimize them (Figure 2.14).

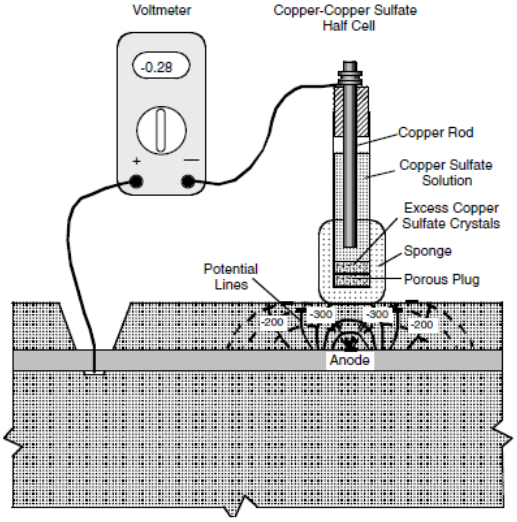

Figure 2.14 Apparatus to measure surface potential associated with corrosion current.

With techniques for corrosion monitoring it could be possible: (1) Provide an advanced alarm of the potential damages that would occur in the structures of production, in case to maintain the existing corrosive conditions; (2) Study a correlation of the changes in the parameter during the process and their effect into the system; (3) Diagnose a particular corrosive problem, identify their causes and the control parameter of the corrosion, such as the pressure, the temperature, pH, etc; (4) Evaluate the effectiveness of a preventive/control technique of the corrosion.

Radioactive/Nuclear Methods: The methods are based on directing ionizing radiation from sources such as radioisotopes and X-ray generators against or through fresh or hardened concrete samples. The radiation collected after interaction with the concrete provides information about physical characteristics such as composition, density, and structural integrity. The radioactive and nuclear methods are fast and accurate, but their use has been limited by the often complex technology involved, high initial costs, and training and licensing requirements.

Short-Pulse Radar Methods: Short-pulse radar (Figure 2.15) is a powerful diagnostic tool with a wide range of applications in the testing of concrete. It is gaining acceptance as a useful and rapid technique for nondestructive detection of delaminations and other types of defects in bare or overlaid reinforced concrete decks. It also shows potential for other applications — such as monitoring of cement hydration or strength development in concrete, study of the effect of various admixtures on curing of concrete, determination of water content in fresh concrete, and measurement of the thickness of concrete members.

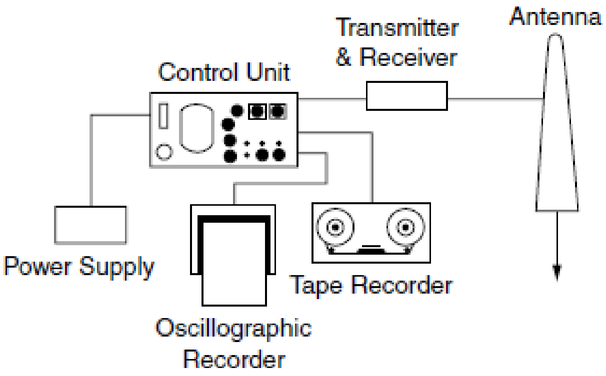

Figure 2.15 Components of a typical short-pulse radar system

Infrared Thermographic Techniques: Infrared thermography, a nondestructive, remote sensing technique, has proved to be an effective, convenient, and economical method of testing concrete (Figure 2.16). It can detect internal voids, delaminations, and cracks in concrete structures such as bridge decks, highway pavements, garage floors, parking lot pavements, and building walls. As a testing technique, some of its most important qualities are that (1) it is accurate; (2) it is repeatable; (3) it is not annoying; and (4) it is economical. By measuring surface temperatures under conditions of heat flow into or out of the material, one can determine the presence and location of any subsurface anomalies.

Figure 2.16 Infrared thermographic radiometer.

Acoustic Emission Methods: Acoustic emissions, which occur in most materials, are caused by irreversible changes, such as dislocation movement, twinning, phase transformations, crack initiation, and propagation, debonding between continuous and dispersed phases in composite materials, and so on. In concrete acoustic emission is due primarily to: 1. Cracking processes; 2. Slip between concrete and steel reinforcement; 3. Fracture or debonding of fibers in fiber-reinforced concrete. Acoustic emission techniques may be very useful in the laboratory to supplement other measurements of concrete properties. However, their use in the field remains problematic.

2.7 Summary

In Table 2.1 are show a summary of all the non destructive methods:

Table 2.1 Summary of nondestructive methods

Inspection method	Parameter measured	Parameter obtained	Advantages	Disadvantages
Visual	Surface condition	-	Cheapest NDT method Instantaneous results	Superficial or little depth (using borescopy or endoscopy)
Load test	Load carrying capacity	Strength of the specimen	Definitive	Very slow and possibly dangerous
Coring	Specific internal dimensions	Strength of the specimen	Definitive dimensions	Measurement only at test point
Ultrasonic	Wave velocity through structure	Strength of the specimen	Relatively quick	Only works on individual masonry blocks due to signal attenuation; no information on major elements
Rebound	Mode shapes (Rebound number)	Hardness of concrete	Gives some indirect measure of current condition	Difficult to quantify data
Penetration resistance	Depth of penetration	Hardness or penetration resistance	The method of testing is relatively simple	Limitations in the size of the specimen
Pull-off	Tensile force to pull	Strength of concrete	Simple and quick to perform	Limitations in the size of the specimen
Impact-echo	Pulse composed of low-frequency waves	Defects of thin concrete structures	Simple and quick to perform	The detection of the effect depends on the contact time
Pull-out	Force required to pull	In-place strength of concrete	Simple and quick to perform	Is a semi-destructive test
Break-off	Force required to pull	In-place strength of concrete	Simple and quick to perform	Limitations in the aggregate size and member thickness
Maturity	Temperature history during curing	Strength gain of concrete	Relatively fast method to know continuously the concrete strength	Calibration curves for every type of concrete are needed.
Resonant frequency	Natural frequency of vibration	Dynamic modulus of elasticity	Provide an excellent means for studying the deterioration of concrete specimens	Small-sized specimens

Combined	Rebound number and pulse velocity	Compressive strength	More accurately	Correlations between the parameters are needed
Magnetic/ Electrical	-	Location of bars, moisture content, corrosion, etc.	Simple and quick to perform	Only superficial analysis No precision
Evaluate Corrosion of Reinforcement	Corrosion status of reinforcing bars	Corrosion status of reinforcing bars	Relatively simple measurement	Requires skill to interpret data
Radioactive/ Nuclear	Radioisotopes and X-ray	Physical characteristics	Generally fast and accurate	Complex technology involved, high initial costs, and training and licensing requirements
Short-Pulse Radar	Short-pulse radar	Detection of delaminations and other types of defects in bare	Quick: can give good penetration; can give good image of internal structure	Poor penetration through clay. Requires skill to understand data
Infrared Thermographic	Surface temperatures	Detect internal voids, delaminations, and cracks	Effective, convenient, and economical	It cannot be determined if a subsurface void is near the surface
Acoustic Emission	Acoustic emissions	Cracking	Very useful in the laboratory to supplement other measurements	Their use in the field remains problematic

3 DESTRUCTIVE TESTING METHODS

3.1 Introduction

In the destructive testing, tests are carried out to the specimen's failure, in order to understand a specimen's structural performance or material behavior under different loads. These tests are generally much easier to carry out, yield more information, and are easier to interpret than nondestructive testing. Destructive testing is most suitable, and economic, for objects which will be mass-produced, as the cost of destroying a small number of specimens is negligible.

So, comparing with nondestructive methods, the destructive tests provide more accurate data to determine the properties of the material under load. Despite of it, sometimes it is not possible to use them (when the material can’t be destroyed) and is when the NDT are useful.

In this research, the destructive methods are focused in obtain three parameters: the compressive strength, the tensile strength and the modulus of elasticity.

Concrete and ceramics typically have much higher compressive strengths than tensile strengths. Composite materials, such as glass fiber epoxy matrix composite, tend to have higher tensile strengths than compressive strengths.

3.2 Compressive strength testing

By definition, the ultimate compressive strength of a material is that value of uniaxial compressive stress reached when the material fails completely. The compressive strength is usually obtained experimentally by means of a compressive test (Figure 3.1).

Figure 3.1 Compressive testing machine in the laboratory

Specimens are loaded to failure in a compression testing machine conforming to EN 12390-4. The maximum load sustained by the specimen is recorded and the compressive strength of the concrete is calculated. Compressive stress and strain are calculated and plotted as a stress–strain curve is plotted by the testing machine and would look similar to the Figure 3.2. This diagram is used to determine elastic limit, proportional limit, yield point, yield strength and, for some materials, compressive strength.

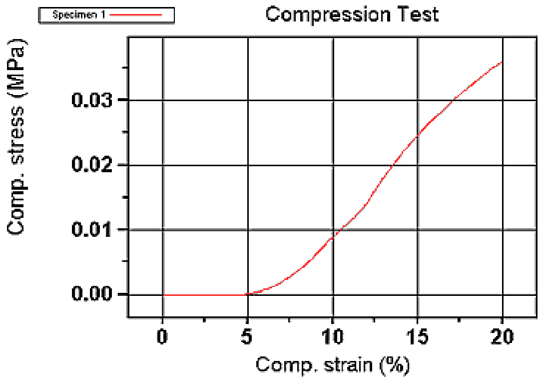

Figure 3.2 Stress-strain curve of a compressive test

The apparatus used for this experiment is the same as that used in a tensile test. However, rather than applying a uniaxial tensile load, a uniaxial compressive load is applied. As can be imagined, the specimen is shortened as well as spread laterally.

<u>Specimen preparation and positioning</u>

Wipe the excess moisture from the surface of the specimen before placing in the testing machine.

Wipe all testing machine bearing surfaces clean and remove any loose grit or other extraneous material from the surfaces of the specimen that will be in contact with the platens.

Do not use packing, other than auxiliary platens or spacing blocks (see EN 12390-4) between the specimen and the platens of the testing machine.

Position the specimens so that the load is applied perpendicularly to the direction of casting.

Centre the specimen with respect to the lower platen to an accuracy of ± 1 % of the designated size of cube or designated diameter of cylindrical specimens.

If auxiliary platens are used, align them with the top and bottom face of the specimen.

With two-column testing machines, cubic specimens should be placed with the trowelled surface facing a column.

<u>Loading</u>

Select a constant rate of loading within the range 0.2 MPa/s to 1.0 MPa/s. Apply the load to the specimen without shock and increase continuously, at the selected constant rate ± 10 %, until no greater load can be sustained.

When using manually controlled testing machines, correct any tendency for the selected rate of loading to decrease, as specimen failure is approached by appropriate adjustment of the controls.

Record the maximum load indicated.

Assessment of type of failure

Examples of the failure of specimen showing that the tests have proceeded satisfactorily are given in Figure 3.3 for cubes and in Figure 3.5 for cylinders. Examples for unsatisfactory failure of specimens are shown in Figure 3.4 for cubes and in Figure 3.6 for cylinders.

If failure is unsatisfactory this shall be recorded with reference to the pattern letter according to figure 3.4 or 3.6 closest to that observed. For cylindrical specimens, failure of the capping before the concrete is an unsatisfactory failure.

Unsatisfactory failures can be caused by:

- Insufficient attention to testing procedures, especially positioning of the specimen;
- A fault with the testing machine.

Results

The compressive strength is given by the equation:

$$f_c = \frac{F}{A_c}$$

Where:

f_c is the compressive strength, in megapascals (newtons per square millimeter).

F is the maximum load at failure, in Newtons.

A_c is the cross-sectional area of the specimen on which the compressive force acts, in square millimeters.

The compressive strength shall be expressed to the nearest 0.5 MPa (N/mm^2).

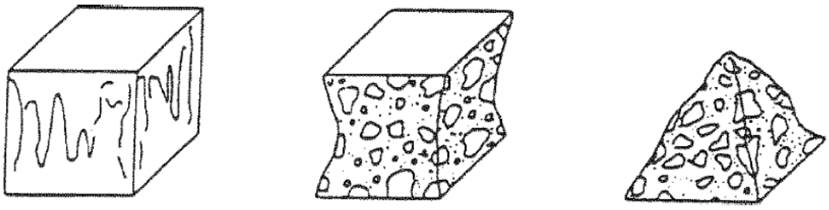

Figure 3.3 Satisfactory failures of cube specimens

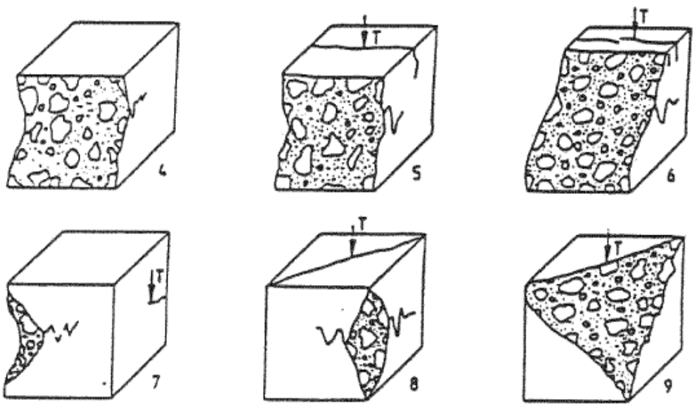

Figure 3.4 Some unsatisfactory failures of cube specimens

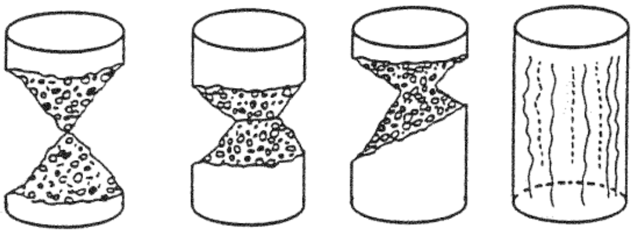

Figure 3.5 Satisfactory failure of cylinder specimen

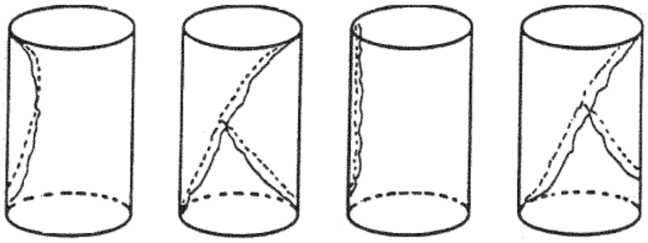

Figure 3.6 Some unsatisfactory failures of cylinder specimens

3.3 Flexural strength testing

Flexural strength, also known as modulus of rupture, bend strength, or fracture strength, a mechanical parameter for brittle material, is defined as a material's ability to resist deformation under load. The flexural strength represents the highest stress experienced within the material at its moment of rupture.

Principle

Prismatic specimens are subject to a bending moment by the application of load through upper and lower roller. The maximum load sustained is recorded an the flexural strength is calculated

Apparatus

The device for applying loads (Figure 3.7) shall consist of:

- two supporting rollers
- two upper rollers carried by and articulated cross member, which devices the load applied by the machine equally between the two rollers.

Three rollers, including the two upper ones, shall be capable of rotating freely around their axis of being inclined in a plane normal to the longitudinal axis of the test specimen.

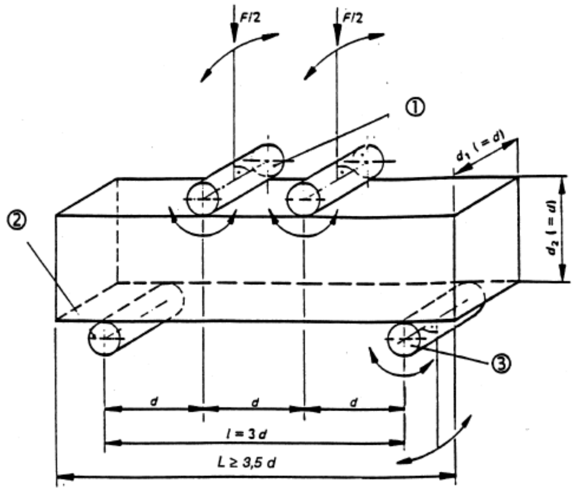

Figure 3.7 Arrangement of loading of test specimen (two-point loading)

Key:

1. Loading roller (capable of rotation and of being inclined)
2. Supporting roller
3. Supporting roller (capable of rotation and of being inclined)

Specimen preparation and positioning

For specimen stored in water, wipe excess moisture from the surface of the specimen before placing in the testing machine.

Wipe clear all testing machine bearing surfaces and remove any loose grit or other material from the surface of the specimen that will be in contact with the rollers.

Place the test specimen in the machine, correctly centered and with the longitudinal axis of the specimen at right angles to the longitudinal axis of the upper and lower rollers.

Ensure that the reference direction of loading in perpendicular to the direction of casting of the specimen

Loading

Do not apply the load until all loading and supporting rollers are resting evenly against the test specimen.

Select a constant rate of stress within the range 0.04 Mpa/s to 0.06Mpa/s. Apply the load without shock and increase continuously, at the selected constant rate ± 1 %, until no greater load can be sustained.

The required loading rate on the testing machine is given by the formula:

$$R = \frac{s \cdot \ d_1 \cdot d_2^2}{l}$$

Where:

R is the required loading rate, in Newtons per second

s is the stress rate, in Megapascals per second

d_1 and d_2 are the lateral dimensions of the specimen, in millimeters.

l is spacing of the lower rollers, in millimeters

Record the maximum load indicated

Results

The flexural strength is given by the equation:

$$f_{ct} = \frac{F \cdot l}{d_1 \cdot d_2^2}$$

Where:

f_{ct} is the flexural strength, in Megapascals.

F is the maximum load, in newtons.

l is distance between the supporting rollers, in millimeters

d_1 and d_2 are the lateral dimensions of the specimen, in millimeters (Figure 3.7)

CASE OF LOADING BY A CENTER-POINT LOAD

In the case where a center-point load is used, the method of test shall be changed in accordance with the following information:

Apparatus

The loading arrangements shall consist of one load-applying roller at mid-span as indicated in Figure 3.8. The load-applying roller shall be free to rotate

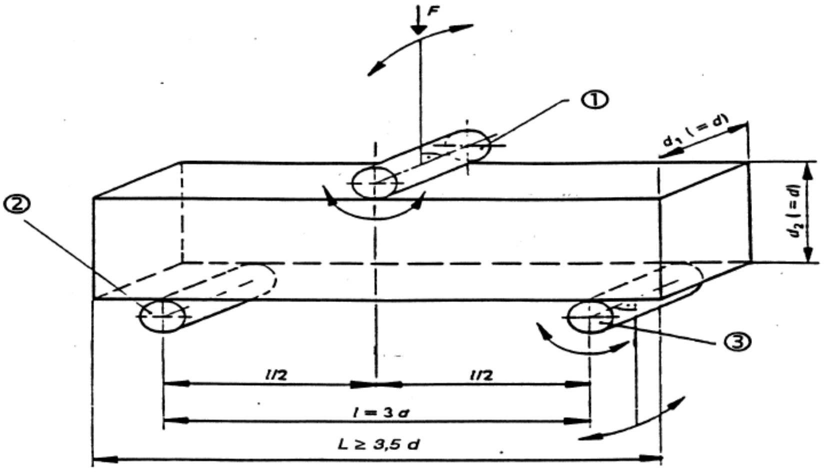

Figure 3.8 Arrangement of loading of test specimen (centre-point loading)

Key:

1. Loading roller (capable of rotation and of being inclined)
2. Supporting roller
3. Supporting roller (capable of rotation and of being inclined)

Loading

The required loading rate shall be determined in accordance with the formula:

$$R = \frac{2 \cdot d_1 \cdot d_2^2 \cdot s}{3 \cdot l}$$

Where:

R is the required loading rate, in Newtons per second

s is the stress rate, in Megapascals per second

d_1 and d_2 are the lateral dimensions of the specimen, in millimeters.

l is is spacing of the lower rollers, in millimeters

Results

The flexural strength is given by the equation:

$$\mathrm{f_{ct}} = \frac{3 \cdot \mathrm{F} \cdot \mathrm{l}}{2 \cdot d_1 \cdot d_2^2}$$

Where:

f_{ct} is the flexural strength, in Megapascals.

F is the maximum load, in newtons.

l is is distance between the supporting rollers, in millimeters

d_1 and d_2 are the lateral dimensions of the specimen, in millimeters (Figure 3.7)

Express the flexural strength to the nearest 0.1 MPa

3.4 Modulus of elasticity

The static modulus of elasticity or Young Modulus is a measure of the stiffness of an elastic isotropic material. It means a measure of the resistance of a material to elastic deformation under load

It is defined as the ratio of the stress along an axis over the strain along that axis in the range of stress in which Hooke's law holds. The tangent modulus of the initial, linear portion of a stress–strain curve is called Young's modulus (Figure 3.7). It can be experimentally determined from the slope of a stress–strain curve created during tensile tests conducted on a sample of the material.

For testing E it is use the same compression testing machine as the compression and tensile strength. And it can be calculated by dividing the tensile stress by the extensional strain in the elastic (initial, linear) portion of the stress–strain curve:

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0}$$

Where

E is the Young's modulus (modulus of elasticity), in Megapascals

F is the force exerted on an object under tension, in Newtons.

A_0 is the original cross-sectional area through which the force is applied, in millimeters.

ΔL is the amount by which the length of the object changes.

L_0 is the original length of the object, in millimeters.

In Figure 3.7 is shown some habitual values of E for different kind of materials

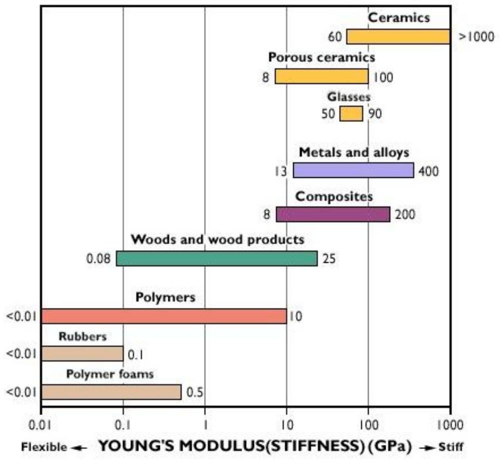

Figure 3.9 Range of E for different types of material

4 EXPERIMENTAL PHASE

4.1 Introduction

The experimental phase is based in doing the nondestructive testing to obtain the values that are interesting for this Thesis and to collect the data from destructive testing in order to compare the results.

The range of materials tested is extensive, from stones to plasters, concrete or bricks. The detailed list of specimens materials tested is presented in the following tables (Tables 4.1, 4.2 and 4.3).

Table 4.1 List of concrete specimens

Concrete specimens	
Code	Specimen material
C8	Normal concrete, lower class - C16/20
C9	HPC (High Performance Concrete)
C10	HPC - fine aggregate + brick powder
UHP I	Ultra High Performance Concrete
UHP II	Ultra High Performance Concrete

In Figure 4.1 are shown an example of the UHP specimens tested in the laboratory.

Figure 4.1 Example of concrete specimens

Table 4.2 List of plaster specimens

Plaster specimens	
Code	**Specimen material**
CE1	Plaster containing pozzolan admixture - type Roubíček
CE2	Baumit MPA 35 - lime/cement plaster
CE3	Baumit GrobPutz Maschinell - core plaster
CE4	Baumit - Thermo Putz - light plaster with perlite
CE5	Baumit Sanova plaster W - restoration plaster
CE6	Baumit Sanova puffer plaster - restoration plaster - support layer
CE7	Baumit MVR Uni - (Porobeton/APC)
CP1	Plaster type I
CP2	Plaster type II
CP3	Plaster type III
CP4	Plaster type IV
CP5	Plaster type V
CP6	Plaster type VI

In Figure 4.2 are shown an example of the plasters specimens tested in the laboratory.

Figure 4.2 Example of plaster specimens

Table 4.3 List of stone and façade wood specimens

Stone and facade wood specimens	
Code	**Specimen material**
CE12	Lime-sand brick
CE15 (NA6)	Sandstone-rough surface
CE16 (NA4)	Sandstone-fine surface
CE17 (NA15)	Claystone/Marlite
CE18	Porobeton P1.8-300
CE19	Facade wood - commercial - cedar
CE20	Facade wood - commercial - spruce

In Figure 4.3 are shown an example of the stone specimens tested in the laboratory.

Figure 4.3 Example of CE specimens

In the family of concrete specimens are included in total 5 samples (normal, high performance and ultra high performance), in the family of plasters are included 7 specimens of plasters, 6 specimens of Baumit (a type of external wall insulation) and a brick specimen, and finally in the family of stones are included in total 6 specimens (sandstones, claystones, porobeton and facade wood).

The tasks realized during the course were the following. In first place it was realized the non destructive test: in some materials were tested by the rebound method and other materials were tested by the pulse velocity method. Then the materials were tested by destructive methods in order to obtain strength parameters. Finally it was made a comparison between the parameters obtained with the nondestructive test with the parameters obtained with the destructive test.

4.2 Nondestructive test done

As it was commented previously in some materials only was tested the pulse velocity method. This was because some materials, like CP or CE (Figure 4.2 and 4.3), were brittle and it was preferable to avoid the risk of breaking the material during the realization of the rebound test in order to be able to do destructive test. Only the hardest materials, like concrete specimens (Figure 4.1), were tested by both experiments.

4.2.1 Pulse velocity test

For this test it was used a Proceq PunditLab+ (Figure 4.4). The instrument is composed by two transducers (cylinders) and an apparatus. One of the cylinders is a pulse generator and transmitter and the second one is the receiver. The apparatus is the responsible of producing and introducing a wave pulse into the material and to read the data when the pulse arrive to the receiver.

Figure 4.4 Pulse Velocity Instrument

The procedure of the test (Figure 4.5) was the following:

1. Measure the length of the specimen on the direction that the pulse it will be transmitted.
2. Introduce the length of the specimen in the apparatus
3. In order to ensure the good contact of the cylinders with the specimen, the application of a special gel between cylinders and specimen is needed.
4. Press the cylinders to the specimen and read the value from the screen. If the measure bar is under 50% the reading is not valid. In this case it is necessary to increase the scale and/or to press with more force to obtain a valid value.
5. Write down the value and repeat the procedure with all the specimens of the material.

Figure 4.5 Procedure of the pulse velocity method

4.2.2 Rebound method

For this test it was used a Proceq SilverSchmidt Type N (Figure 4.6). The main components include the outer body, the plunger, the hammer mass, and the main spring (Figure 2.4).

Figure 4.6 Rebound Hammer

The procedure of the test (Figure 4.7) was the following:

1. Place the specimen in a suitable support in relation that it doesn't create extra rebound.
2. Push the hammer to different points of the surface of the specimen 10 times.
3. With the electronic device it is possible to make an average of the values.
4. Write down the value and repeat the procedure with all the specimens of the material.

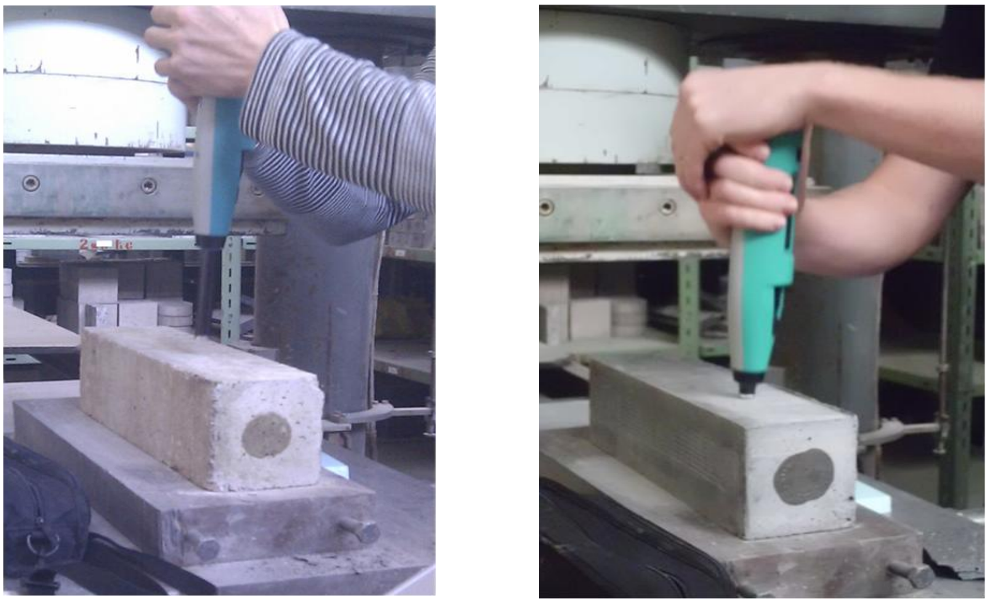

Figure 4.7 Procedure of the rebound method

4.3 Destructive test done

Once the specimens were tested by nondestructive methods the following step was tested them by destructive test (Figure 4.8). Some of the tests were realized by the author of this thesis and some others were realized by the workers of the laboratory. The parameters obtained in these experiments were the flexural strength, the compressive strength and Young Modulus.

Figure 4.8 Destructive test done

4.4 Obtained values

As it was explained during the test there were obtained different values for the material specimens. In this subchapter are presented them in the following tables of results. First are presented the results of concrete specimens, then the results of plaster specimens and finally the results of stones specimens.

4.4.1 Concrete specimens

In Table 4.4 are shown the results for the concrete specimen C8, C9 and C10 and in Table 4.5 the results of Ultra High Performance Concrete specimens

Table 4.4 Table of results Concrete Specimens C8-C9-C10.

C8-9-10 Specimens		Non destructive measurements		Destructive measurements	
Code	**nº specimen**	**Pulse velocity method (m/s)**	**Rebound method (Mpa)**	**Flexural strength (MPa)**	**Compressive strength (Mpa)**
C8	1	1680	31,5	4,0	35,6
	2	1715	30,0	3,7	34,3
	3	1544	30,5	4,0	34,7
	Average	**1646,3**	**30,7**	**3,9**	**34,9**
C9	1	1239	83,0	8,4	87,2
	2	1203	66,5	8,8	89,4
	3	1224	59,5	8,3	90,5
	Average	**1222,0**	**69,7**	**8,5**	**89,0**
C10	1	1316	65,5	6,6	140,0
	2	1376	66,1	6,5	119,9
	3	1327	74,5	9,2	105,0
	Average	**1339,7**	**68,7**	**7,4**	**121,6**

Table 4.5 Table of results Concrete Specimens UHP.

UHP Specimens		Nondestructive measurements		Destructive measurements	
Code	**nº specimen**	**Pulse velocity method (m/s)**	**Rebound method (MPa)**	**Flexural strength (MPa)**	**Compressive strength (Mpa)**
UHP I	3.1	5125	75,5	11,8	123,8
	3.2	5310	73,0	11,6	122,4
	3.3	5440	72,5	11,4	119,8
	Average	**5292**	**73,7**	**11,6**	**122,0**
UHP II	3.-1	5065	64,5	11,1	116,3
	3.-2	5175	63,5	10,9	115,4
	3.-3	5225	58,5	10,5	112,1
	Average	**5155**	**62,2**	**10,8**	**114,6**

4.4.2 Plaster specimens

In Table 4.6 are shown the results for the plaster specimens CE and in Table 4.7 the results of plaster specimens CP

Table 4.6 Table of results Plasters Specimens CE

CE Specimens		Non destructive measurements	Destructive measurements	
Code	**nº specimen**	**Pulse velocity method (m/s)**	**Flexural strength (MPa)**	**Compressive strength (Mpa)**
CE1	1	1660	0,67	1,48
	2	1641	0,43	1,45
	3	1238	0,31	0,93
	4	1649	0,69	1,98
	5	1594	0,39	1,36
	6	1268	0,33	1,39
	7	1476	0,62	1,52
	8	-	-	-
	Average	**1503,7**	**0,49**	**1,44**
CE2	1	1907	1,92	2,69
	2	1760	1,40	1,94
	3	2003	1,66	2,72
	4	1759	0,60	1,87
	5	1702	1,05	1,67
	6	2041	1,52	2,34
	7	1953	1,12	1,92
	8	2067	1,34	2,26
	Average	**1899,0**	**1,33**	**2,18**
CE3	1	2325	1,56	2,87
	2	1978	1,31	2,23
	3	1965	1,40	2,29
	4	2081	1,09	2,50
	5	2028	1,20	2,85
	6	2259	1,42	2,65
	7	2081	1,21	2,42
	8	2273	1,32	2,60
	Average	**2123,8**	**1,32**	**2,55**

CE4	1	1692	1,09	2,08
	2	1608	0,23	1,49
	3	1535	0,41	1,66
	4	1632	0,95	1,83
	5	1574	0,57	1,49
	6	1582	0,63	1,52
	7	1516	0,52	1,67
	8	1558	0,75	1,84
	Average	**1587,1**	**0,64**	**1,70**
CE5	1	1930	1,67	3,50
	2	2008	1,22	4,33
	3	2028	1,52	4,89
	4	1978	1,63	3,67
	5	1841	1,62	3,68
	6	1978	1,42	3,89
	7	2003	1,55	4,12
	8	1965	1,66	4,05
	Average	**1966,4**	**1,54**	**4,02**
CE6	1	2374	2,94	5,91
	2	2416	2,71	5,38
	3	2416	2,89	5,30
	4	2342	2,50	5,73
	5	2428	2,81	6,75
	6	2435	2,58	5,67
	7	2344	2,85	5,82
	8	2410	2,92	5,94
	Average	**2395,6**	**2,77**	**5,81**
CE7	1	1953	2,04	3,70
	2	1819	1,60	2,65
	3	1741	1,50	2,41
	4	1769	1,25	2,20
	5	1749	1,53	2,41
	6	1821	1,42	2,46
	7	1850	1,55	2,65
	8	1712	1,72	2,85
	Average	**1801,8**	**1,58**	**2,67**

Table 4.7 Table of results Plaster Specimens CP.

CP Specimens		**Non destructive measurements**	**Destructive measurements**	
Code	**nº specimen**	**Pulse velocity method (m/s)**	**Flexural strength (MPa)**	**Compressive strength (Mpa)**
CP1	1	1680	0,35	1,19
	2	1715	0,43	1,22
	3	1544	0,32	1,32
	4	1590	0,52	1,33
	5	1660	0,28	1,06
	6	1689	0,43	1,26
	Average	**1646,3**	**0,39**	**1,23**
CP2	1	1239	0,29	1,43
	2	1203	0,35	1,41
	3	1224	0,29	1,31
	4	1249	0,34	1,26
	5	1212	0,38	1,18
	6	1205	0,29	1,15
	Average	**1222,5**	**0,32**	**1,29**
CP3	1	1316	0,47	1,91
	2	1376	0,48	1,88
	3	1327	0,35	1,85
	4	1366	0,46	1,85
	5	1322	0,40	2,09
	6	1331	0,33	1,73
	Average	**1339,7**	**0,42**	**1,88**
CP4	1	1566	0,39	1,64
	2	1535	0,38	2,04
	3	1624	0,47	2,08
	4	1541	0,44	1,87
	5	1599	0,51	2,57
	6	1585	0,51	2,13
	Average	**1575,0**	**0,45**	**2,05**
CP5	1	1450	0,42	1,58
	2	1460	0,45	1,71
	3	1515	0,41	1,54
	4	1501	0,44	2,22
	5	1461	0,41	2,40
	6	1463	0,45	2,08
	Average	**1475,0**	**0,43**	**1,92**

CP6	1	1487	0,26	3,53
	2	1524	0,31	3,11
	3	1428	0,21	3,56
	4	1530	0,25	3,89
	5	1470	0,29	3,75
	6	1439	0,46	4,04
	Average	**1479,7**	**0,30**	**3,65**

4.4.3 Stones and facade wood specimens

In Table 4.8 and 4.9 are shown the results for the stone and facade wood specimens CE.

Table 4.8 Table of results Plaster Specimens CE.

Plaster CE Specimens		Non destructive measurements	Destructive measurements	
Code	**nº specimen**	**Pulse velocity method (m/s)**	**Flexural strength (MPa)**	**Compressive Strength (Mpa)**
CE12	1	3100	3,50	48,60
	2	3106	3,98	51,80
	3	3178	3,71	54,10
	Average	**3128,0**	**3,7**	**51,5**
CE15 (NA6)	1	2442	1,18	8,75
	2	2277	1,31	8,59
	3	2356	1,33	8,85
	4	2384	1,28	8,79
	5	2442	1,30	8,75
	6	2236	1,27	8,72
	Average	**2356,2**	**1,28**	**8,74**
CE16 (NA4)	1	3367	6,09	36,50
	2	3231	6,17	35,40
	3	3300	6,17	34,50
	4	3204	5,92	35,90
	5	3274	6,07	33,60
	6	3146	5,95	36,90
	Average	**3253,7**	**6,06**	**35,47**
CE17 (NA15)	1	3578	13,2	46,8
	2	3515	10,0	46,0
	Average	**3546,5**	**11,6**	**46,4**
CE18	1	1935	0,506	1,4
	2	1992	0,534	1,6
	3	1907	0,549	1,8
	Average	**1944,7**	**0,5**	**1,6**

Table 4.9 Table of results facade wood specimens

Wood Specimens		Non destructive measurements	Destructive measurements	
Code	**nº specimen**	**Pulse velocity method (m/s)**	**Flexural strength (MPa)**	**Young Modulus (Gpa)**
CE19	I	1949	78,7	10,7
	II	1962	99,3	11,8
	III	1937	62,7	9,1
	Average	**1949,3**	**80,2**	**10,5**
CE20	A	2109	70,8	10
	B	2024	96,8	11,4
	C	2045	91,2	13,9
	Average	**2059,3**	**86,3**	**11,8**

4.5 Comparison of results

The comparison is done by doing some graphs representation for each material. In each graph is represented in one of the axis one parameter obtained with nondestructive methods (rebound method or pulse velocity method) and in the other axis one parameter obtained with destructive methods (flexural strength, compressive strength or Young Modulus). Once the data is plotted in the graph the next step is draw the best approximation of the points with a trendline. In this investigation the only approximations that are taking into account are linear or polynomials of second degree to simplify the results and the conclusions.

4.5.1 Concrete specimens

UHP

In the first place it is compared the flexural strength with the pulse velocity method (Figure 4.9). As it can be seen the best approximation with the obtained data is a polynomial function of second order.

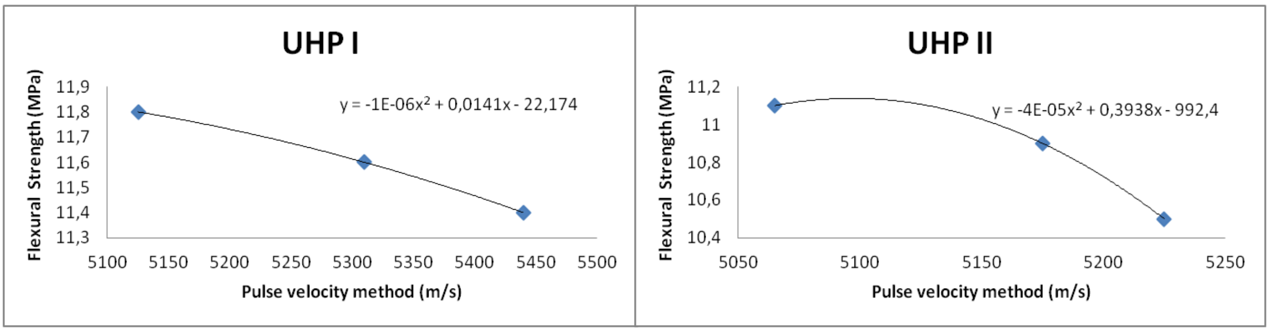

Figure 4.9 UHP-Comparison flexural strength vs pulse velocity method

In the comparison of compressive strength with the pulse velocity method (Figure 4.10) it is visible that the best approximation of the points it is again a polynomial function of second order.

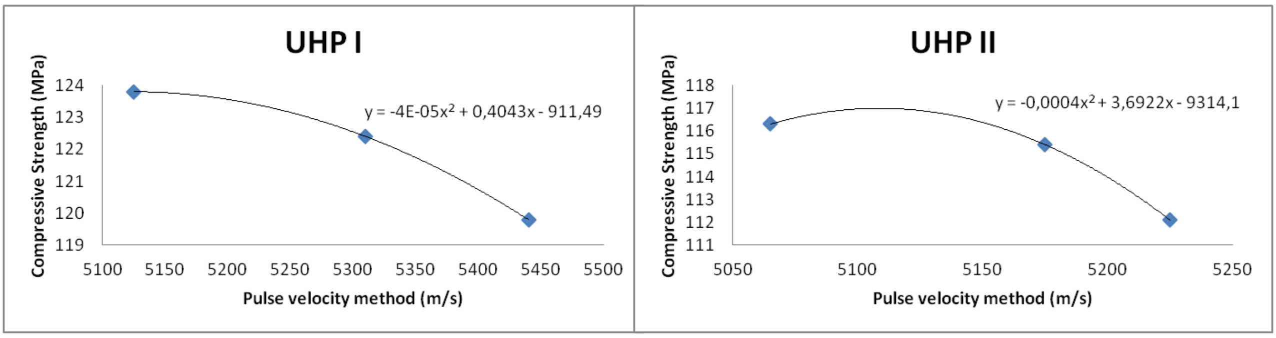

Figure 4.10 UHP-Comparison compressive strength vs pulse velocity method

And in the comparison of rebound method with the flexural (figure 4.11) and compressive strength (Figure 4.12) it is shown that the best approximation is also a polynomial of second order.

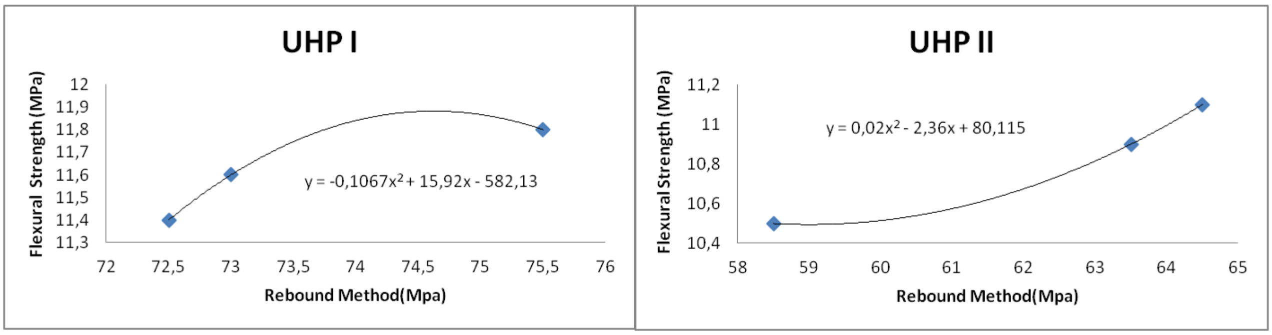

Figure 4.11 UHP- Comparison flexural strength vs rebound method

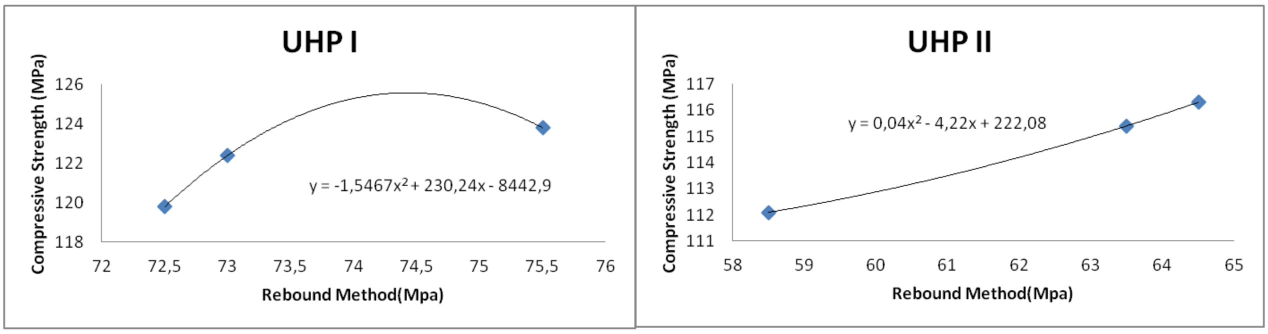

Figure 4.12 UHP- Comparison compressive strength vs rebound method

As it can be seen the approximation of compressive strength with both nondestructive test respectively are similar for both specimen UHP. The differences are not so remarkable. In the other hand in the case of flexural strength the differences between both specimens are more significant. This is because there is a difference of almost 7Mpa in the flexural strength between the first sample UHP and the second one. This difference can be explained because of changes in the composition of both specimens or because of mistakes in the measurement procedure.

So, it can be considered that the relation of compressive strength for Ultra High Performance Concrete is good enough and can be use for future investigation. Nevertheless in the case of flexural strength it would be necessary to do more test in order to obtain better approximations.

Despite of these conclusions in followings measurement it would be better test more specimens of the material in order to have more points in the graphic representation of the comparison. With more points it would be possible to ensure that the relations obtained are correct and them are not an unreal approximation because of the lack of data.

C8

In figure 4.13 are represented the results for the normal concrete specimen.

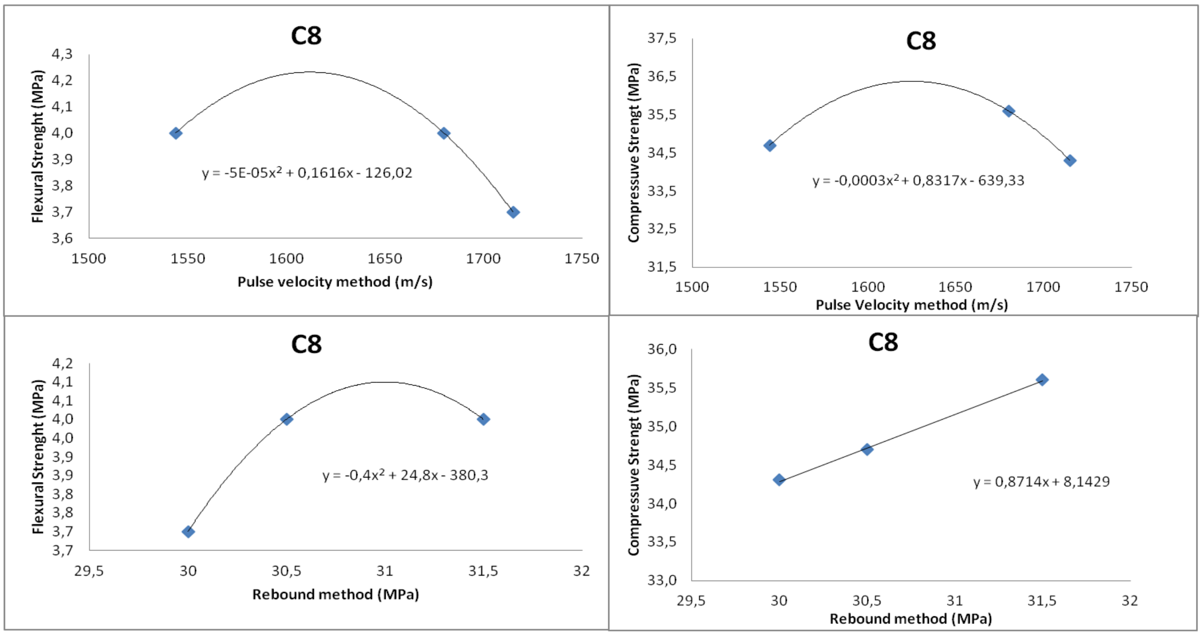

Figure 4.13 Comparison of C8 specimens

All the graphs follow a polynomial of second order relation except for the relation Compressive strength versus rebound method that follows a linear relation.

C9

In Figure 4.14 is represented the results for High Performance Concrete HPC.

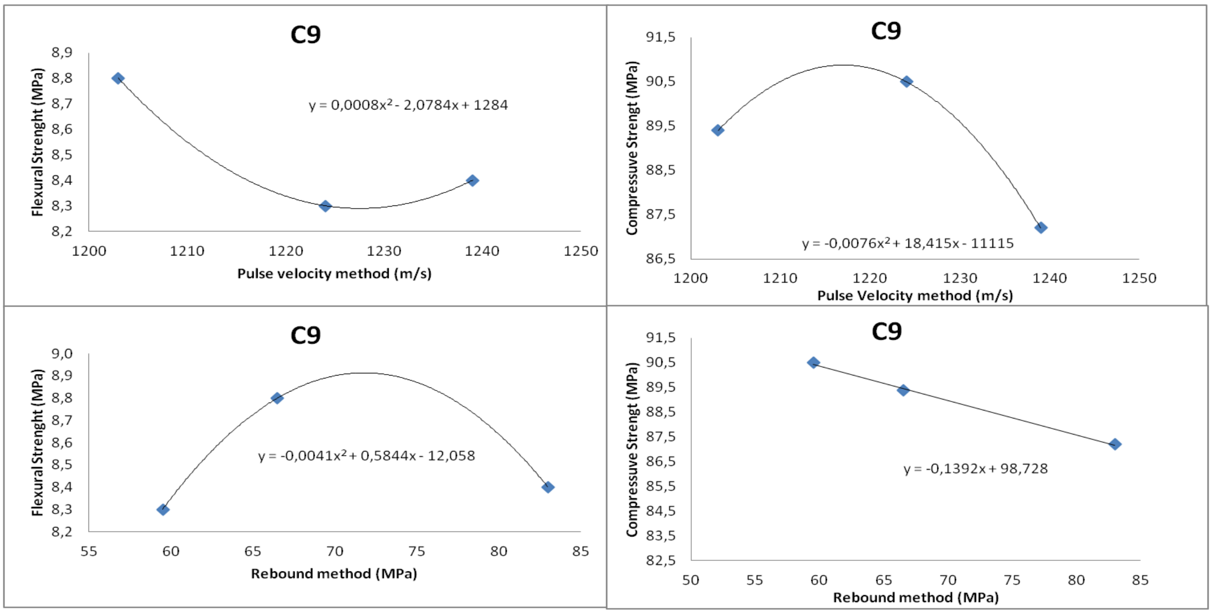

Figure 4.14 Comparison of C9 specimens

The relations of this specimens are the same than the before material: all the graphs follow a polynomial of second order relation except for the relation Compressive strength versus rebound method that follows a linear relation. But the differences are visible in the magnitude of the equations that are no equal in both materials. This is because the HPC specimen has around the double compressive strength than the normal concrete and around three times more flexural strength.

C10

In Figure 4.15 is represented the results for HPC + brick power specimen.

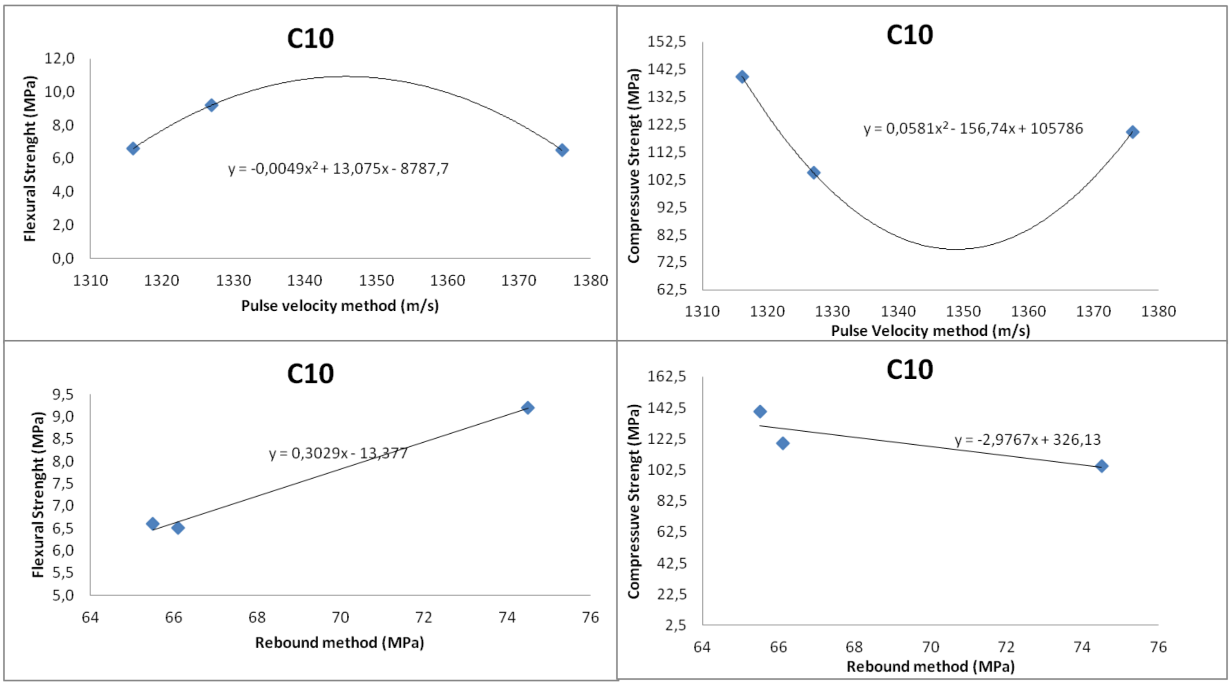

Figure 4.15 Comparison of C10 specimens

The remarkable difference between the results of this material C10 and the last two, C8 and C9, is that the relation of flexural strength and rebound method is not polynomial of second order anymore, in this case is a linear relation. This difference and the variance of the values of the equations it is explained because the composition of C10 (fine aggregate + brick power) increase the compressive strength over 37%

Despite of the results make sense in the C8, C9 and C10 specimens happen the same as UHP specimens, with more points it would be possible to ensure that the relations obtained are correct and them are not an unreal approximation because of the lack of data.

4.5.2 Plaster CE specimens

In the next Figures (from Figure 4.16 to Figure 4.22) are shown the comparison of flexural strength and compressive strength versus pulse velocity method for each type of CE specimen tested- As it was said in Table 4.2, CE1 is a plaster specimen and the others (C2 to C7) are different types of Baumit specimens. For each type of material there were 7 specimens, so it is considered enough data to get a relation between the different parameters under consideration.

CE1

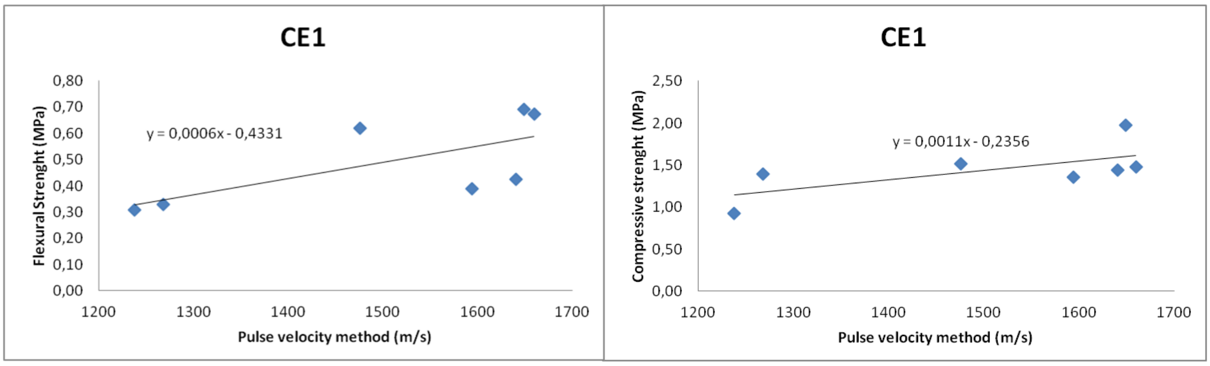

Figure 4.16 Comparison CE1 specimens

CE2

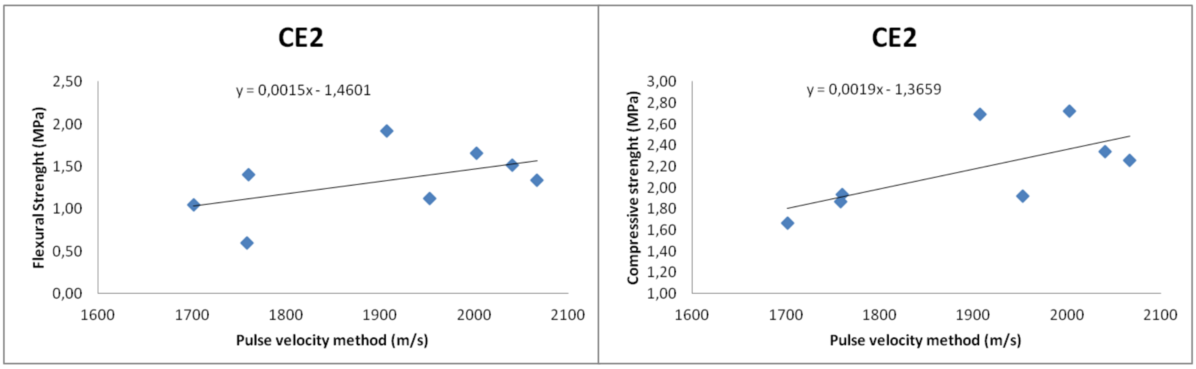

Figure 4.17 Comparison CE2 specimens

CE3

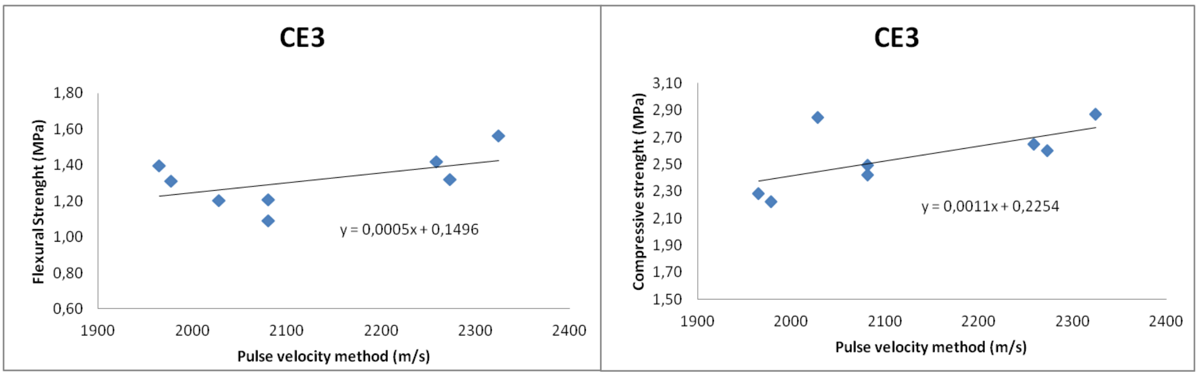

Figure 4.18 Comparison CE3 specimens

CE4

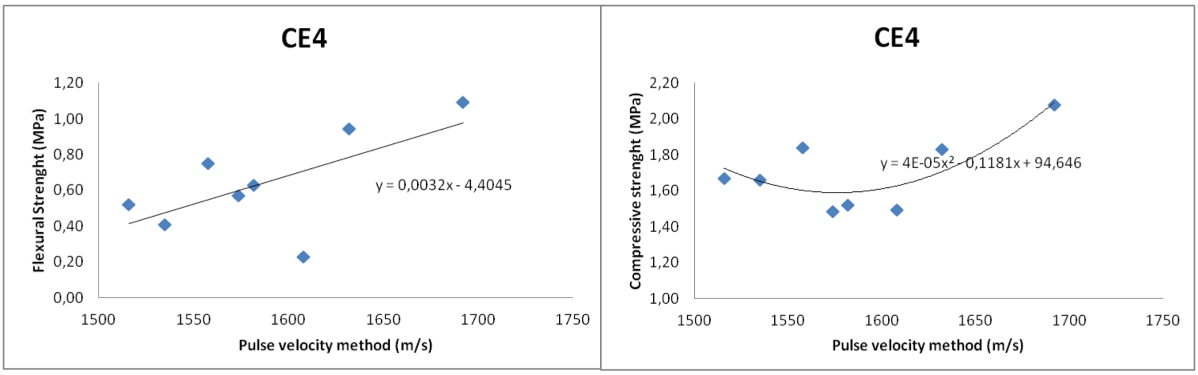

Figure 4.19 Comparison CE4 specimens

CE5

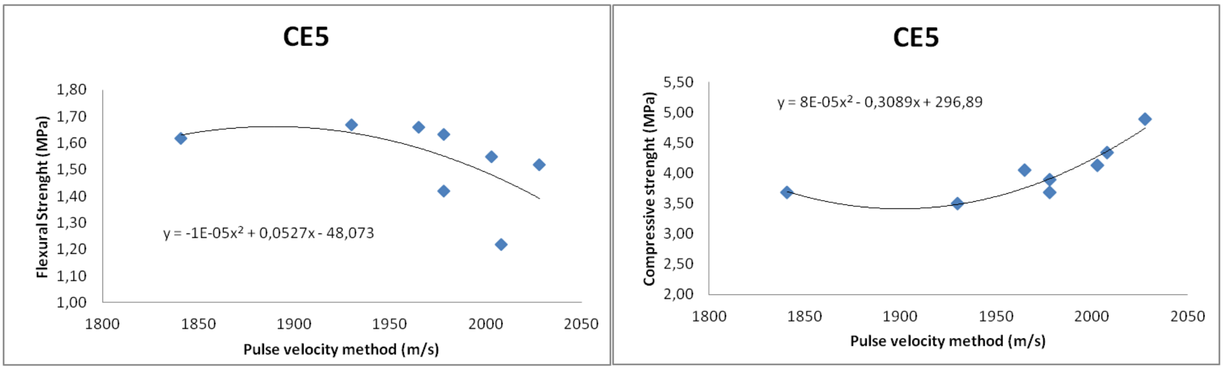

Figure 4.20 Comparison CE5 specimens

CE6

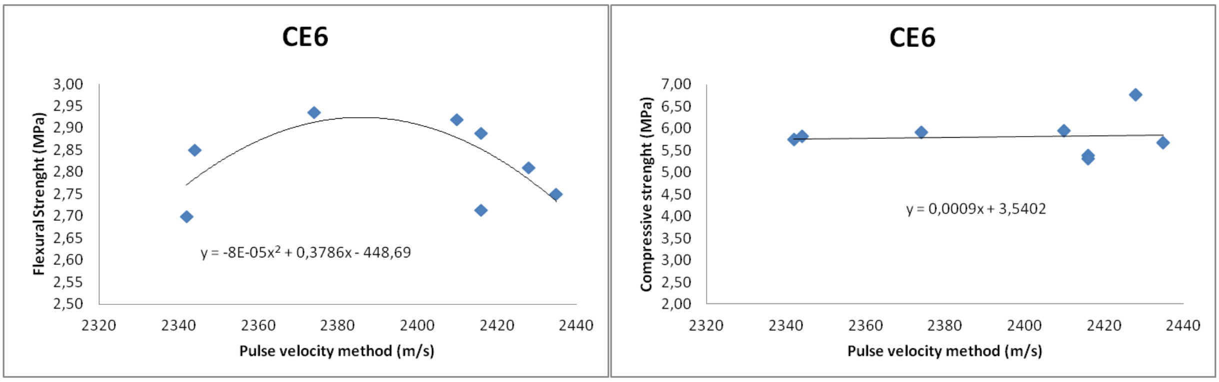

Figure 4.21 Comparison CE6 specimens

CE7

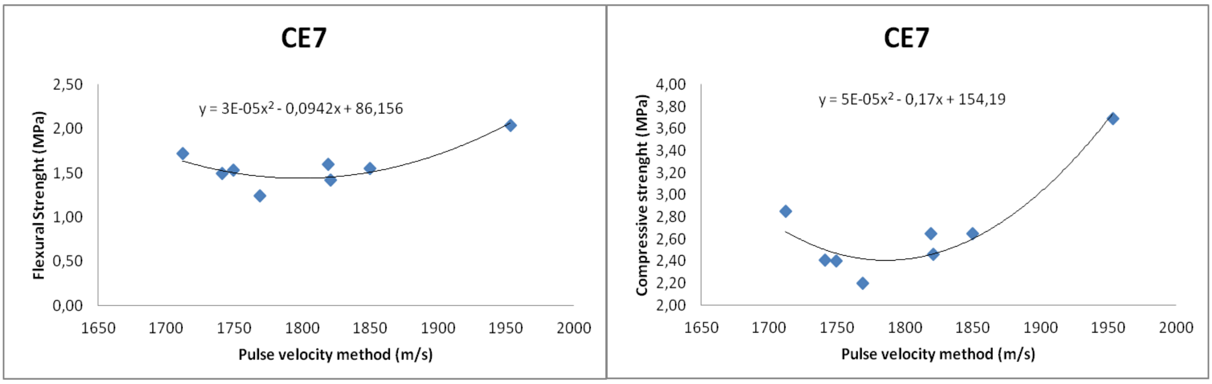

Figure 4.22 Comparison CE7 specimens

As it can be seen in the previous figures some of the relations are linearly dependents and some others polynomial of second order.

Relative to the Baumit specimens (C2 to C7) it is observed that there aren't similarities of the relations of the parameters between the materials. This is because that different composition of the Baumit specimens changes the resistance parameters and, due to this, the relations found. So it is necessary to be sure which kind of Baumit is under investigation in order to use the correct relation, and not to use relation of materials with different resistance or strength characteristics.

Relative to the other material tested (C1) has linear relation in both comparisons. Despite of that it is observed that the points are scattered and maybe a linear relation is not the best approximation. So two proposals are considered as the best ones for further investigation. The first one is to repeat the testing with other specimens of the material and to compare the results obtained. And the other is use the data presented in this report but use another approximation like for example a polynomial function of third order.

4.5.3 Plaster CP specimens

In the next Figures (from Figure 4.23 to Figure 4.28) are presented the comparison of flexural strength versus pulse velocity method and compressive strength versus pulse velocity method for each type of plaster specimen tested (CP1 to CP6). As it was said in Table 4.2, the specimens are different type of Plasters. For each type of material there were 6 specimens, so it is considered enough data to get a relation between the different parameters under consideration.

<u>CP1</u>

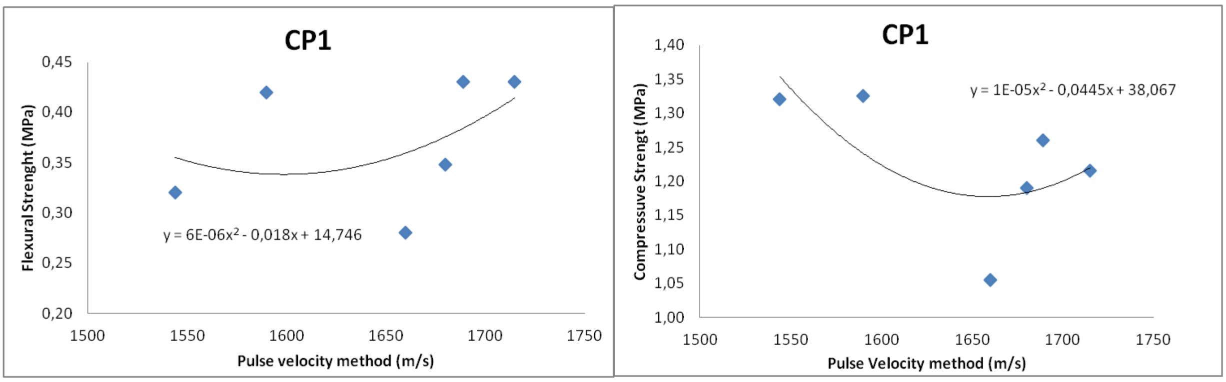

Figure 4.23 Comparison CP1 specimens

CP2

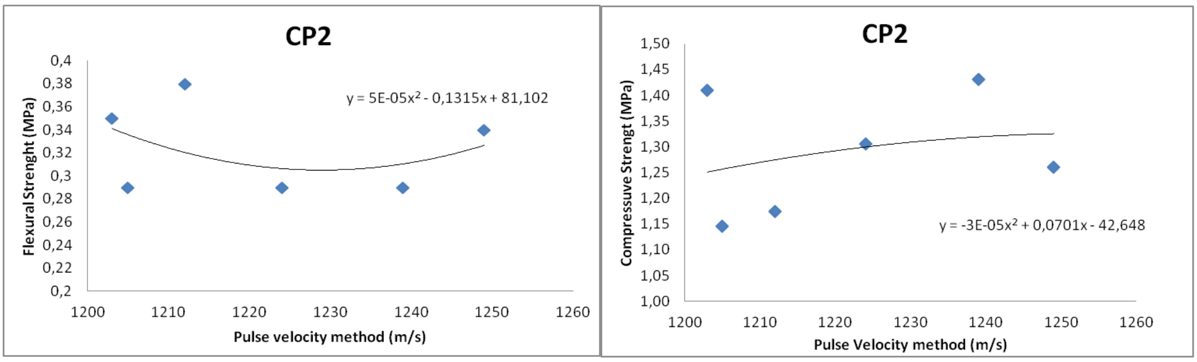

Figure 4.24 Comparison CP2 specimens

CP3

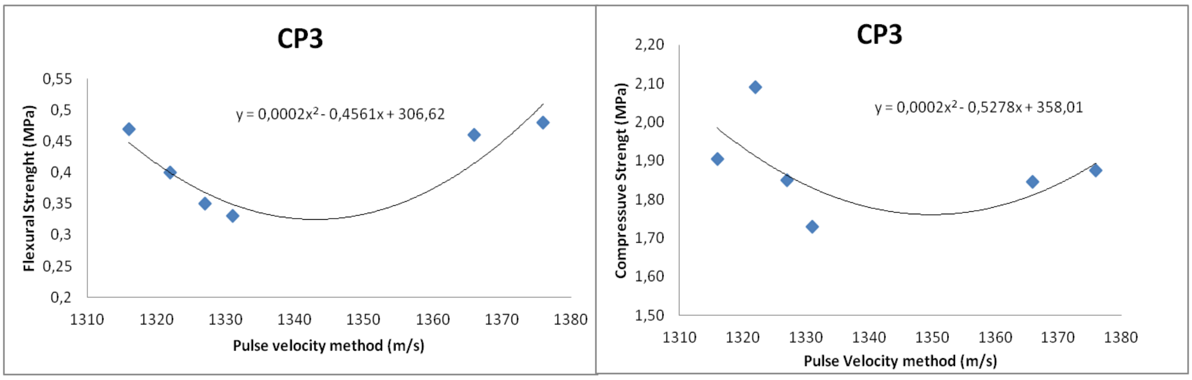

Figure 4.25 Comparison CP3 specimens

CP4

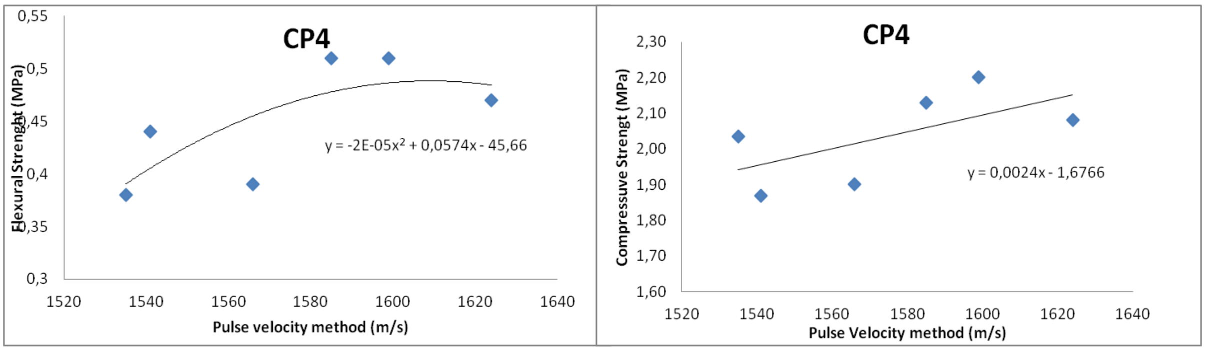

Figure 4.26 Comparison CP4 specimens

CP5

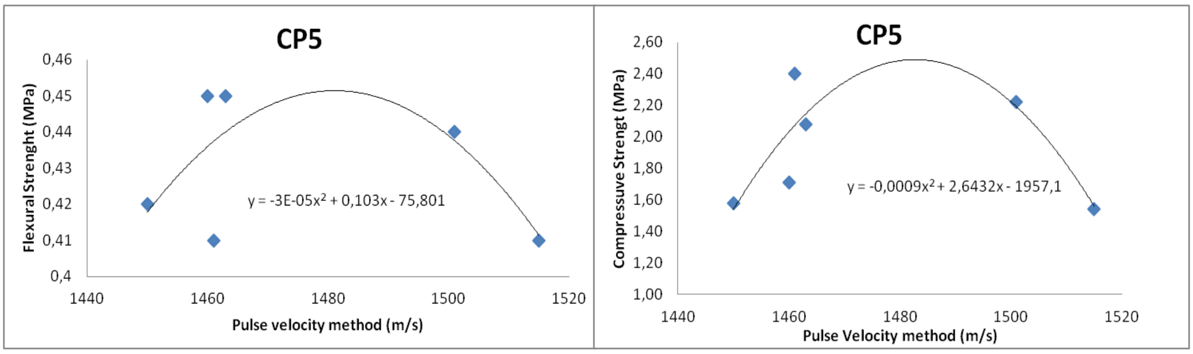

Figure 4.27 Comparison CP5 specimens

CP6

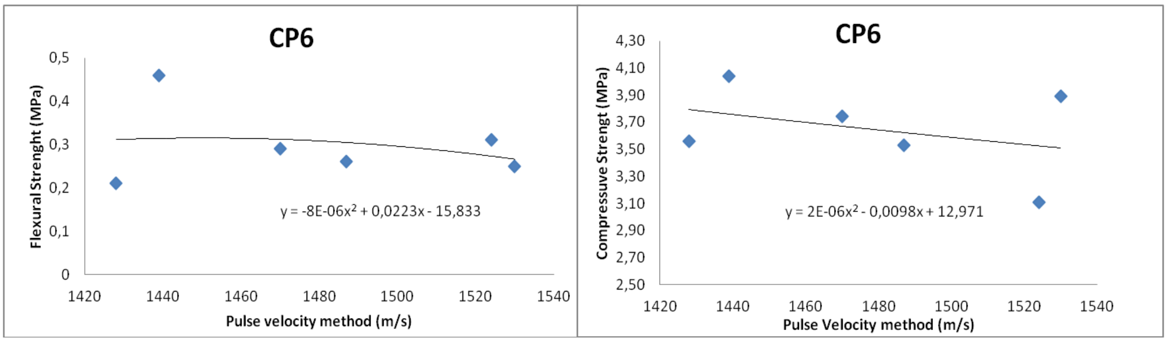

Figure 4.28 Comparison CP6 specimens

As it can be seen in the previous Figures there are random relations for the obtained parameters.

CP1 and CP2 have a polynomial of grade 2 relation but the approximations don't pass through the points. In this specimens seem that a polynomial of grade 3 relation would be more suitable. In contrast CP3 and CP5 have good approximation with a polynomial relation of second degree. The last two materials CP4 and CP5 have a polynomial relation in the flexural strength graph and a linear approximation in the compressive strength. But all of them are not so good and another approximation like, for example, a polynomial function of third order would be more appropriate for the obtained data.

4.5.4 Stone and facade wood specimens

CE12

In the figure 4.29 is shown the results obtained for the lime-sand brick.

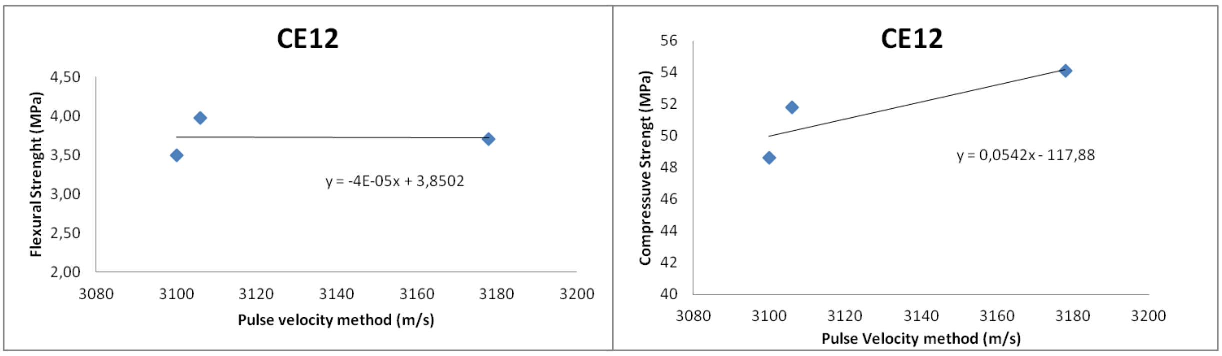

Figure 4.29 Comparison CE12 specimens

For this type of material a linear relation is obtained for both comparisons. It would be also possible accept as a good approximation a polynomial of second order, but because of both of the results are very near from each other, it is considered in this case that the approximation showed in Figure 4.29 are the correct one. But as it happened in other type of materials, with only three points it is not possible to ensure that the approximation is accurate enough or if it is follow this relation.

CE15 & CE16

Figures 4.30 and 4.31 are shown the obtained relations for the sandstone specimens. The first one is for sandstone with rough surface and the second one with fine surface.

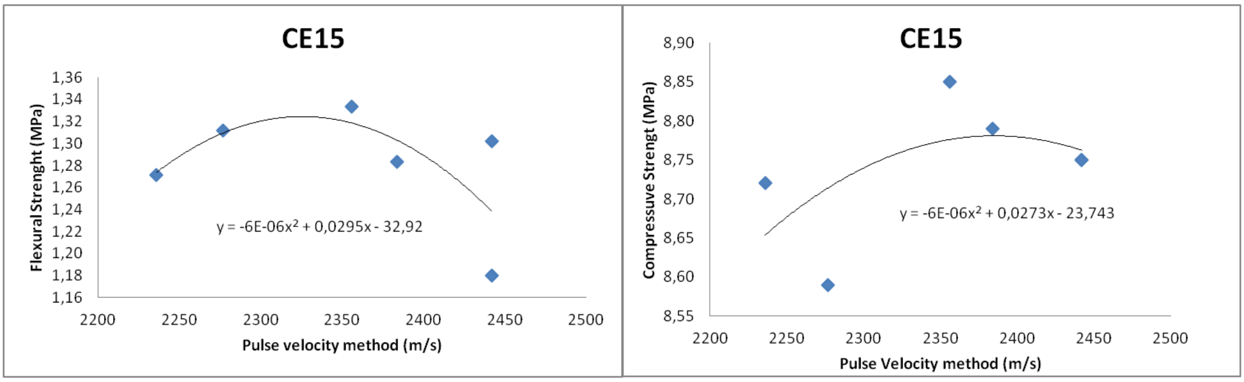

Figure 4.30 Comparison CE15 specimens

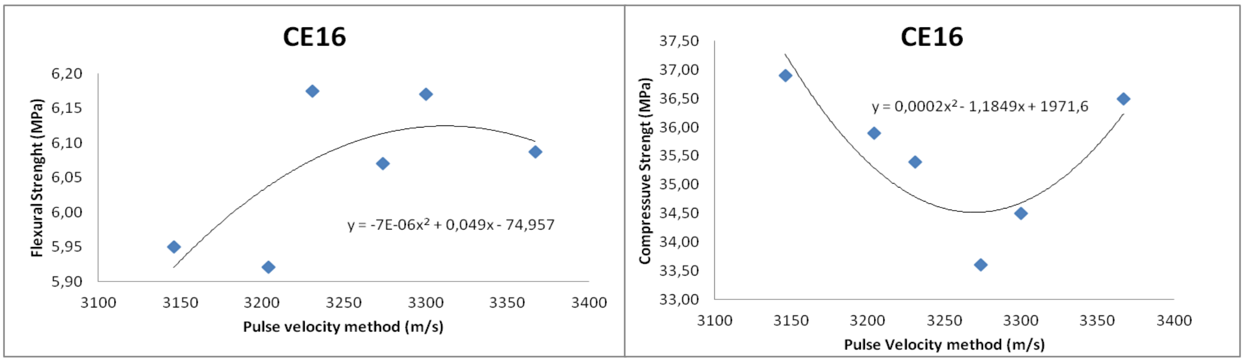

Figure 4.31 Comparison CE16 specimens

As it can be seen in Figures 4.30 and 4.31 for both type of sandstone are obtained polynomial relations of second order but the equations are not the same. This is because, as it can be seen in Table 4.6, in the sandstone with fine surface it had measured higher values of flexural and compressive strength than in the sandstone with tough surface: while in the flexural strength are observed a difference of 5 times more, in the compressive strength 4 times higher.

Although the approximation of polynomial function is accepted, in fact they are not very precise so, as it happens in C1 specimen, another type of approximation could be considered.

CE17

In Figure 4.32 are shown the relations in the case of the Claystone/Marlite specimens.

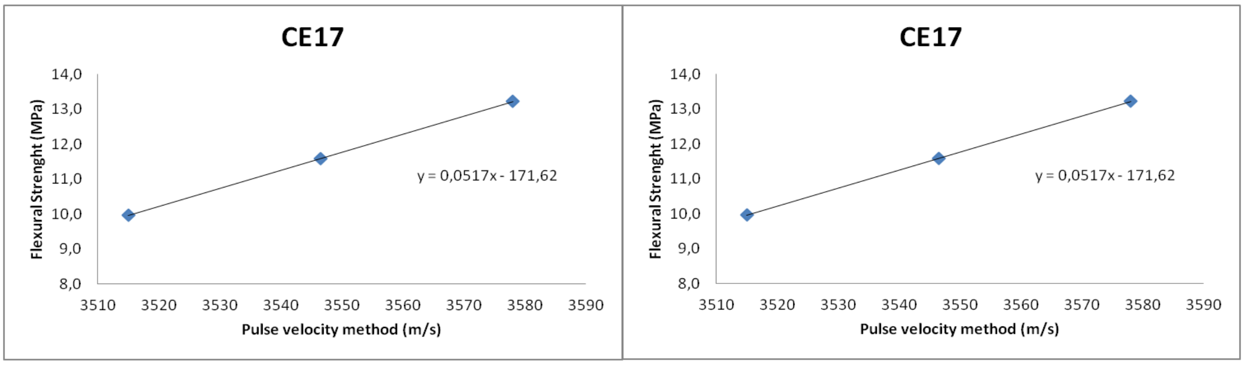

Figure 4.32 Comparison CE17 specimens

CE18

In the Figure 4.33 is represented the results for the testing of the specimen CE18.

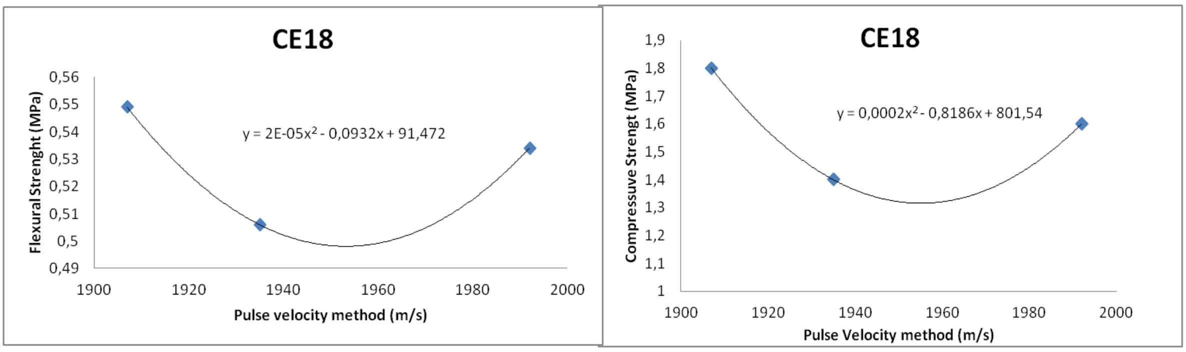

Figure 4.33 Comparison CE18 specimens

The representation of Figure 4.32 and 4.33 show a linear and polynomial of second degree respectively. But because of it was only tested 3 specimens it would be necessary make another testing for this type of materials in order to ensure that the relations are accurate enough and to obtain a more precise relation.

CE19 & CE20

In the Figure 4.34 and 4.35 are represented the relation obtained for the facade wood specimens.

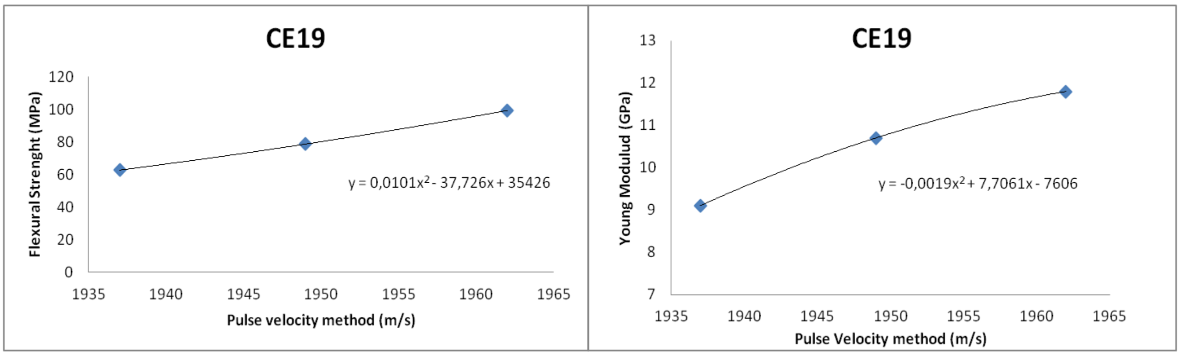

Figure 4.34 Comparison CE19 specimens

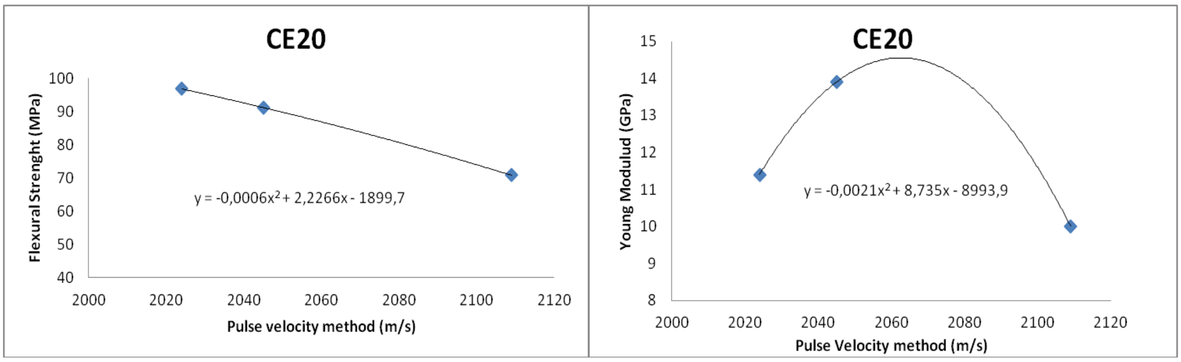

Figure 4.35 Comparison CE20 specimens

For facade wood specimens the relations within the parameters are a polynomial of second order but there are some differences in the equations for both types of material. The reason is second one, spruce wood, have higher values of resistance characteristics than the first one, cedar wood. Despite of the approximations pass through the points it would be necessary to check with more number of specimens if the equations are still keeping the same magnitudes.

5 CONCLUSIONS AND RECOMMENDATIONS

The objective of this thesis was obtain some relation between parameters obtained with nondestructive methods with parameters obtained with destructive methods in order to have some relation to compare both kinds of methods. The NDT used were the rebound method and the pulse velocity method. And the parameters obtained with DT were the flexural strength, the compressive strength and de Young Modulus. The relations considered were linear or polynomial of second degree approximations.

After the work done during the course, plenty of setbacks, it is possible to say that this research has been successful. Despite of what was commented in chapter 4.5, that it has to be done some modifications in the approximations or some of the test have to be repeated with more number of specimens, some relations of nondestructive test and destructive test have been reached.

With this research is it has become apparent again that it is possible to make direct relations of NDT parameter with DT parameters. In other words, knowing some parameters due to NDT it is possible to evaluate the strength and the resistance of a material like if a DT was done. Due to this, as it was commented in chapter 2 and 3, with NDT it is possible to, using the obtained relations, get an approximation of the real strength parameters without carrying out destructive test that in some cases, like historical buildings are impossible to be carried out.

5.1 Recommendations for further work

In this subchapter are commented the experiments and Works that from the point of view of the author of this thesis should be realized during the course 2014-2015 in order to complete the study done during the course 2013-2014 and to define a proper direct relation between the parameters obtained by nondestructive test with the parameters obtained by destructive for all type of materials.

- Relative to the materials tested

In the present course were tested a wide range of materials: concrete, plasters, stones and wood specimens. So the investigation contemplated different kinds of materials in relation of historical buildings. Despite of that in order to complete the research it would be necessary to add other types of materials like ceramics or mortars.

Moreover, there were some materials tested that as it was commented in the thesis it would be necessary to repeat the tests with more specimens in order to check if the obtained relations are accurate enough. In this situation are the UHP specimens, some stone materials and the façade wood specimens.

- Relative to the relations obtained

In this investigation it was only considered linear and polynomial of second order approximations in other to simplify the relations within the parameters. But in some cases it is visible that no one of these approximations is suitable with the obtained data. So, in future research it would be necessary to consider the option of using other types of approximation like polynomial of third order that have better adjust with the obtained data. In this situation are C1 specimens, Plasters CP materials and both sandstones specimens.

- Relative to the destructive parameters obtained

The parameters obtained with destructive test were compressive strength, flexural strength and Young Modulus. It is considered as enough data in order to know the conditions of a building when checking its resistance.

No in all the specimens was obtained the three destructive parameters. In all of them the flexural and compressive strength was obtained, except for the facade wood specimens that instead of compressive strength it was obtained the Young Modulus. And specimens are the only one where the Young modulus was given. So for next test it would be necessary obtain the maximum number of destructive parameter for each type of material in order to have a more completed study.

- Relative to the nondestructive parameters obtained

The test done with the specimens during the course was the rebound method and the pulse velocity method. The pulse velocity method was tested in all the materials but the rebound it was not possible because of some specimens were too fragile. So, in future experiments it would be necessary try to find a way to do the rebound method even in the fragile materials order to have a more completed study.

For the same reason it is recommended to do other nondestructive methods like penetration resistance methods, the pull-off test and combined methods. The penetration test provides a measure of the hardness or penetration resistance of the material that can be related to its strength, with pull-off test it is possible to obtain the compressive strength and about combined methods it can be used the SONREB Method: By knowing the rebound number and pulse velocity, the compressive strength is estimated.

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