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Non-Destructive Testing of Concrete: A Review of Methods

J. Helal, M. Sofi, P. Mendis.
University of Melbourne, Australia

Email: massoud@unimelb.edu.au

ABSTRACT: This paper reviews the most common non-destructive testing (NDT) methods of concrete structures as utilized by the structural engineering industry. The fundamentals of NDT methods are explored in regards to their potential, limitations, inspection techniques and interpretations. The factors that influence the success of NDT methods are discussed and ways to mediate their influence are recommended. Reference is made to standard guidelines for the application and interpretation of the discussed NDT methods. NDT of concrete was found to be gaining increasing acceptance as a means of evaluating the strength, uniformity, durability and other properties of existing concrete structures. Perceptions of NDT inadequacy were attributable to lack of understanding construction materials and NDT methods themselves. The intent of this paper is to address these concerns by identifying and describing the most common successful methods of NDT as applied to concrete structures.

1 INTRODUCTION

Non-destructive testing (NDT) is defined as the course of inspecting, testing, or evaluating materials, components or assemblies without destroying the serviceability of the part or system (Workman & O. Moore, 2012). The purpose of NDT is to determine the quality and integrity of materials, components or assemblies without affecting the ability to perform their intended functions. Non-destructiveness ought not to be confused with non-invasiveness. Testing methods that do not affect the future usefulness of a part or system are considered to be non-destructive even if they consist of invasive actions. For example, coring is a common NDT method that is employed to extract and test specimens from concrete components in order to determine the properties of in-situ concrete. Coring alters the appearance of the component and marginally affects its structural integrity. If done correctly, coring maintains the serviceability of the structural component and is thus considered to be non-destructive.

Destructive testing explores failure mechanisms to determine the mechanical properties of material such as yield strength, compressive strength, tensile strength, ductility and fracture toughness. NDT methods explore indications of properties without reaching component or assembly failures. Extensive attempts and advancements have been made to develop NDT methods capable of indicating mechanical, acoustical, chemical, electrical, magnetic, and physical properties of materials. One of the earliest documented attempts of NDT dates to the 19th century where cracks were detected in railroad wheels by means of acoustic tap testing (Stanley, 1995). More sensitive, reliable and quantifiable NDT methods have expansively emerged in recent years.

NDT methods have materialized as a response to the need for structural damage detection and prevention. The extensive use of NDT is driven by economics and safety. In a pre-emptive attempt to eradicate the problems associated with structural deterioration, novel in-site testing techniques have been invented to allow for the assessment of concrete during the construction, commissioning and servicing lifecycle stages of a structure.

The major factors that influence the success of a non-destructive survey are depth of penetration, vertical and lateral resolution, contrast in physical properties, signal-to-noise ratio and existing information about the structure (McCann & Forde, 2001). The understanding of material properties and the key issues associated with their application in structural engineering is imperative for the success of any NDT method. The steps to choosing an adequate NDT method are (Shull, 2002):

- Understanding the physical nature of the material property or discontinuity to be inspected;
- Understanding the underlying physical processes that govern the NDT method;

- Understanding the physical nature of the interaction of the probing field with the test material
- Understanding the potential limitations of available NDT technology;
- Considering economic, environmental, regulatory and other factors.

There is a wide range of NDT methods which are used by the civil and structural engineering industry. While there appears to be ample technical literature regarding NDT of concrete, there is a lack of collaboration between civil engineers, NDT researchers and specialists. The intent of this paper is to bridge the gap by identifying and describing the most common methods of NDT as applied to concrete structures.

2 NON-DESTRUCTIVE TESTNG METHODS

2.1 *Surface hardness methods*

Non-destructive surface hardness methods are non-invasive procedures that investigate strength characteristics of material. The two categories that define concrete surface hardness techniques are indentation methods and rebound methods. These methods attempt to exploit empirical correlations between strength properties of concrete and surface hardness as measured by indentation or rebound. Originating in the 1930 (Jones, 1969), indentations methods are no longer common in the civil engineering industry, whereas rebound methods are frequently applied to investigate concrete strength characteristics with reference to standard guidelines on testing and interpretation.

The most commonly used surface hardness procedure is the standard rebound hammer test. The test was developed in 1948 by Swiss engineer Ernst Schmidt and is commonly referred to as the Schmidt Rebound Hammer (Kolek, 1969). Upon impact with the concrete surface, the rebounded hammer records a rebound number which presents an indication of strength properties by referencing established empirical correlations between strength properties of concrete (compressive and flexural) and the rebound number.

The fundamental understanding of impact and rebound relates to the theory of wave propagation. A compression wave is propagated when the surface of the concrete is disturbed by the plunger (σ_i). The reaction force propagates a reflected compression wave through the plunger (σ_r). The ratio of the wave amplitudes (σ_r / σ_i) is found to be proportional to the rebound number which could be empirically correlated to compressive and flexural strength (Akashi & Amasaki, 1984).

Operation of the Standard Rebound Hammer requires less mechanical skills as compared to other methods of NDT. A visual examination of the concrete surface should be conducted prior to the test in order to identify a smooth surface suitable for testing. The test can be conducted in any directional angle where calibration charts are used to mitigate the different effects of gravity (Fig. 1). The hammer is pressed against the concrete surface until a spring loaded mass is released causing the plunger to impact against the surface and rebound a distanced measured by a slide indicator (Fig. 2). The measured distance is referred to as the rebound number.

Figure 1. NDT of concrete by Schmidt Rebound Hammer (As adapted from http://www.ntu.edu.sg/)

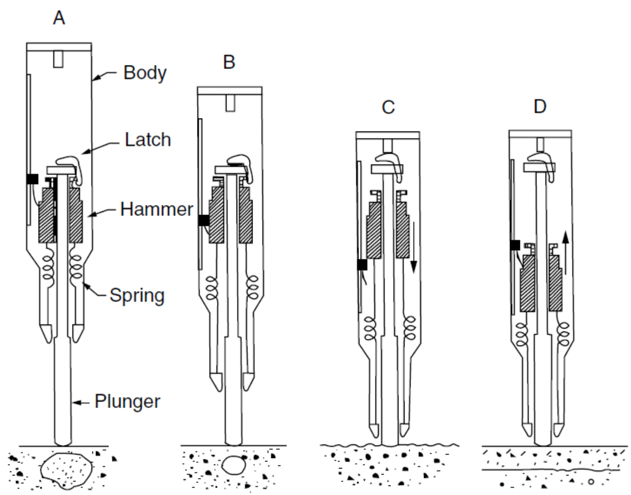

Figure 2. Schematic diagram of Schmidt rebound hammer procedure (Malhotra, 2004)

Empirical correlations are provided by the manufacturer to relate the rebound number to concrete strength properties; however, the testing conditions of the manufacturer might be dissimilar to the conditions present. Therefore, it is recommended to conduct a test-specific correlation procedure where a number of concrete cylinders ranging in strength are prepared and tested by both Standard Rebound Hammer and compression-testing machine. The results of the two tests are then integrated into a simple regression analysis model which yields an empirical correlation by means of ordinary least squares. The following publications present standard guidelines for the application and interpretation that govern the standard rebound test:

- ASTM C 805: Standard Test Method for Rebound Number of Hardened Concrete;
- BS EN 12504-2:2012: Testing Concrete in Structures - Non-destructive Testing - Determination of Rebound Number.

The Standard Rebound Hammer provides a simple, easy and inexpensive method to estimate concrete strength properties. However, the results of the test on concrete are affected by various factors such as smoothness of the surface, geometric properties of the test specimen, age of the test specimen, surface and internal moisture conditions of the concrete, type of coarse aggregate, type of cement, type of mold and carbonation of the concrete surface (Malhotra, 2004). Strength estimation from rebound readings of specimens similar to correlation curve specimens are achieved within an accuracy of 15% to 20% (Concrete Institute of Australia, 2008). It is therefore recommended that the standard rebound hammer test be used as a method of testing variability of strength properties between concrete samples rather than as a substitute for standard compression testing.

2.2 *Penetration resistance method*

Penetration resistance methods are invasive NDT procedures that explore the strength properties of concrete using previously established correlations. These methods involve driving probes into concrete samples using a uniform force. Measuring the probe's depth of penetration provides an indication of concrete compressive strength by referring to correlations. Due to the insignificant effect of the penetration resistance methods on the structural integrity of the probed sample, the tests are considered to be non-destructive despite the disturbance of the concrete during penetration.

The most commonly used penetration resistance method is the Windsor probe system. The system consists of a powder-actuated gun, which drives hardened allow-steel probes into concrete samples while measuring penetration distance via a depth gauge (Fig. 3). The following publications present standard guidelines for the application and interpretation that govern penetration testing:

- ASTM C 803-02: Standard Test Method for Penetration Resistance of Hardened Concrete;
- BS 1881-207 Testing Concrete - Recommendations for the assessments of concrete strength by near-to-surface tests.

The penetration of the Windsor probe creates dynamic stresses that lead to the crushing and fracturing of the near-surface concrete (Fig. 4). A cone-shaped zone develops upon penetration, which encompasses fracturing and is resisted by the compression of the adjacent concrete. The resistance is empirically correlated to probe penetration depth; however, empirical relationships provided by manufacturers often yield unsatisfactory results. Therefore, test-specific correlation procedures should be conducted utilizing penetration methods and compression-testing machine in order to achieve more accurate correlation charts.

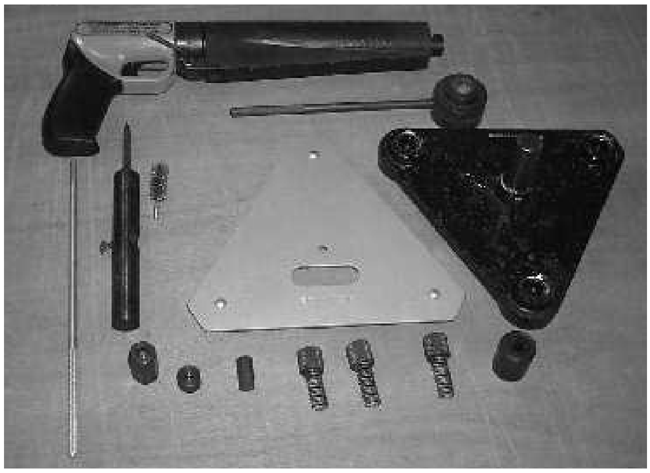

Figure 3. Components of the Windsor Probe System (As adapted from http://www.ntu.edu.sg/)

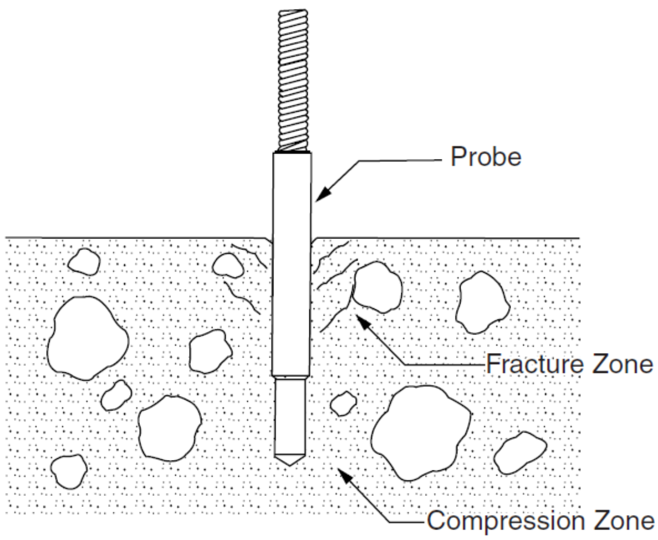

Figure 4. Schematic diagram of typical concrete failure mechanism during probe penetration (Malhotra & Carette, 2004)

The factors that contribute to within-test variability are attributable to operator error, equipment error, size of aggregates and the heterogeneous nature of concrete (Malhotra & Carette, 2004). The most significant factor that affects within-test variability is aggregate size. For example, a 5% coefficient of variation is expected for testing samples of 20mm aggregate size; whereas, a 14% coefficient of variation is expected for samples of 55mm aggregate size (Concrete Institute of Australia, 2008). Nevertheless, variations in the estimated early strength of concrete are low to moderate, which provides a reasonable degree of accuracy and certainty for the removal of formwork in concrete constructions. Additionally, the number of factors contributing to within-test variability are fewer than those of other NDT procedures such as surface hardness methods. The Windsor probe system is quick, cheap and simple to operate. As with surface hardness methods, the penetration resistance methods do not yield absolute values of strength and must therefore be used as a method of testing variability of strength properties between concrete samples.

2.3 *Pull-out resistance methods*

Pull-out resistance methods measure the force required to extract standard embedded inserts from the concrete surface. Using established correlations, the force required to remove the inserts provides an estimate of concrete strength properties. The two types of inserts, cast-in and fixed-in-place, define the two types of pull-out methods. Cast-in tests require an insert to be positioned within the fresh concrete prior to its placement. Fixed-in-place tests require less foresight and involve positioning an insert into a drilled hole within hardened concrete.

Pull-out resistance methods are non-destructive yet invasive methods which are commonly used to estimate compressive strength properties of concrete. The most commonly used pull-out test method is the LOK test developed in 1962 by Kierkegarrd-Hansen (Kierkegaard-Hansen, 1975). The test requires an insert embedment of 25mm to insure sufficient testing of concrete with coarse aggregates (Fig. 5). The force required to remove the insert is referred to as the "lok-strength", which in other pull-out resistance methods is referred to as the pull-out force.

The following publications present standard guidelines for pull-out resistance testing:

- ASTM Standard C 900-13a: Standard Test Method for Pullout Strength of Hardened Concrete;
- BS 1881-207 Testing Concrete - Recommendations for the assessments of concrete strength by near-to-surface tests.

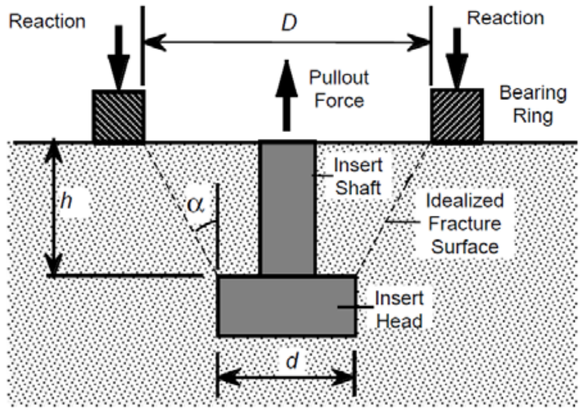

Figure 5. Schematic diagram of typical pull-our resistance methods (Carino, 2004)

The pull-out force is resisted by normal stresses and shear stresses acting on the insert surface. The non-uniform three-dimensional state of stress initiates a concrete failure mechanism, which lacks a consensus in its understanding. Analytical and experimental studies have attempted to gain understanding of the fundamental failure mechanism and have been successful in presenting substantial correlations between pull-out force and compressive strength (Bickley, 1982; Keiller, 1982). The average value for the coefficient of variation for the pull-out test has been found to be around 8% (Carino, 2004). The factors that affect result variability are maximum aggregate size, cement mortar percentage, type of insert and depth of embedment (Concrete Institute of Australia, 2008). These factors can be mediated by conducting test-specific correlation charts which match in characteristics with the expected concrete samples of interest.

2.4 *Pull-off resistance method*

The pull-off test is an in-situ strength assessment of concrete which measure the tensile force required to pull a disc bonded to the concrete surface with an epoxy or polyester resin. The pull-off force provides an indication of the tensile and compressive strength of concrete by means of established empirical correlation charts.

The most commonly used pull-off test is the 007 Bond Test. The test consists of a hand operated lever, bond discs, an adjustable alignment plate, and force gauges (Fig. 6). The disc is bonded to the concrete surface by a high strength adhesive and is attached to the hand operated lever by a screw. After leveling the adjustable alignment plate, tension force is applied by the lever and measured by the force gauge (Fig. 7). The pull-off tensile strength is calculated by dividing the tensile force at failure by the disc area and is used to determine the compressive strength of concrete by using previously established empirical correlations. The following publications present standard guidelines for pull-off resistance testing:

- ASTM D 4541-109e1: Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers;
- BS 1881-207: Testing Concrete - Recommendations for the assessments of concrete strength by near-to-surface tests.

Figure 6. A typical setup of pull-out resistance NDT methods (Adapted from http://www.ndtjames.com)

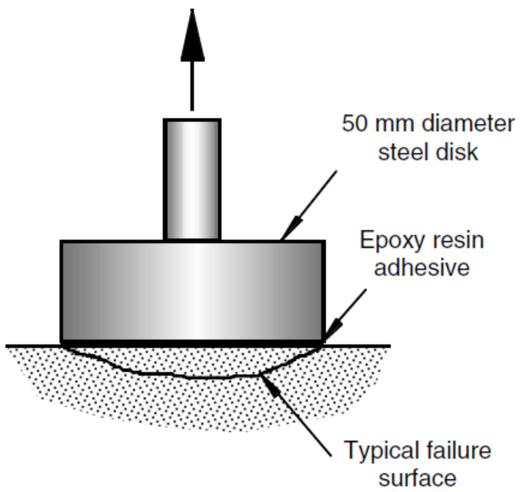

Figure 7. Schematic diagram of pull-out resistance NDT methods (Henderson, Basheer, & Long, 2004)

The main advantage of pull-off test methods is that they are simples, quick and could be used to test a wide range of construction settings. A significant limitation is the curing time required for the adhesive, which is generally around 24 hours. Another limitation relates to the human error in surface preparation which may cause the adhesive to fail.

The results for tensile strength are often within 20% of the true tensile strength (Concrete Institute of Australia, 2008). The factors that most contribute to the variability of results are the size and type of coarse aggregates (Henderson, Basheer, & Long, 2004). It is recommended to develop correlation charts using samples that match testing conditions and to conduct the test several times using different sized disks in order to increase confidence by repeatability.

2.5 *Resonant frequency test method*

Resonant frequency methods are non-invasive nondestructive tests that are conducted to determine material properties by measuring their natural frequency of vibration. The two categories of resonant frequency methods are resonant frequency by vibration and resonant frequency by impact.

The natural frequency of a vibrating structural member is a function of its dimensions, dynamic modulus of elasticity and density. Therefore, measuring either the transverse or longitudinal natural frequency of vibrations of a structural member of know dimensions and material allows the determination of its modulus of elasticity (Eq. 1 & 2) (Rayleigh, 1945). It should be noted that the following equations were determined according to homogenous, isotropic and perfectly elastic systems. The conditions are not met in the testing of in-situ concrete; however, the equations still provide an accurate estimate of material properties.

$$N = (m^2 k / 2\pi L^2)\sqrt{E/d} \quad (1)$$

$$E = (4\pi^2 L^4 N^2 d)/(m^4 k^2) \quad (2)$$

where E = dynamic modulus of elasticity; d = density of the material; L = length of the specimen; N = fundamental flexural frequency; k = radius of gyration; and m = a constant (4.73 for the fundamental mode of vibration).

The system comprises of an oscillator which generates mechanical vibrations and sensors that detect the vibrations (Fig. 8). The three most commonly used sensors are displacement sensors, velocity sensors and accelerometers.

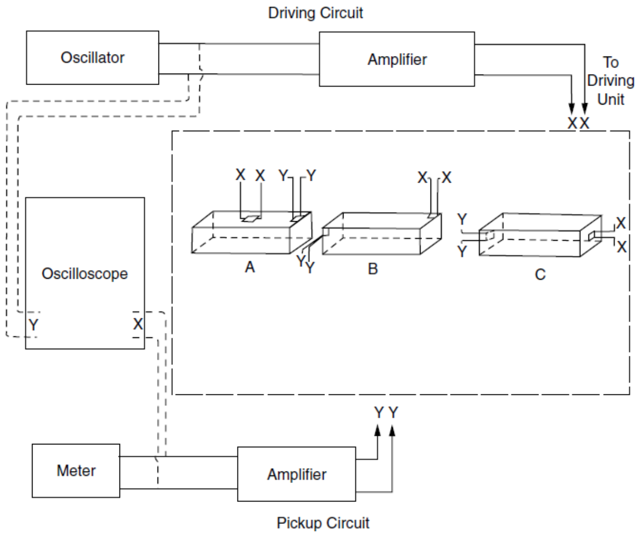

Figure 8. Schematic diagram of a typical apparatus for the forced resonance method showing driver and pickup positions for the three types of vibration. (A) Transverse resonance. (B) Torsional resonance. (C) Longitudinal resonance. (Adapted from ASTM C 215-85)

The standard guideline on testing and interpreting resonant frequency methods is ASTM Standard C 215-85: Standard Test Method for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens. The dynamic modulus of elasticity provides an indication of the mechanical integrity of structural components. Dynamic modulus of elasticity is generally higher than the static modulus of elasticity, which is the recommended parameter in design calculations. The factors affecting resonant frequency and dynamic modulus of elasticity are the concrete mix proportions, aggregate properties, structural specimen size and curing conditions. These factors should be taken into account when testing structural elements that are dissimilar to the conditions outlined in ASTM C215-85. Nevertheless, resonant frequency methods provide an excellent means for studying the effects of extreme temperature changes and loading.

2.6 *Maturity test method*

The maturity method is a NDT technique for determining strength gain of concrete based on the measured temperature history during curing. The maturity function is presented to quantify the effects of time and temperature. The resulting maturity factor is then used to determine the strength of concrete based on established correlations. The maturity method has various applications in concrete construction such as formwork removal and post-tensioning.

Temperature versus time is recorded by means of thermocouples inserted into fresh concrete (Fig. 9). The measured time history could be used to compute a maturity index which provides a reliable estimate of early age concrete strength as a function of time (Saul, 1951) . The standard guideline on the testing and interpretation of the maturity method is ASTM C 1074-11: Standard Practice for Estimating Concrete Strength by Maturity Method.

Figure 9. Maturity test apparatus with thermocouple (Adapted from http://www.humboldtmfg.com)

The factors that lead to variability in testing are aggregate properties, cement properties, water-cement ratio and curing temperature (Concrete Institute of Australia, 2008). Before attempting to estimate in-situ strength of concrete, laboratory testing on concrete samples of similar characteristics must be performed in order to develop the correct maturity function while minimizing the effect of the aforementioned factors. Temperature probe locations must be carefully selected to measure a representative temperature of the entire concrete section.

2.7 *Permeation test method*

The permeability of aggressive substances into concrete is the main cause for concrete deterioration. Permeability represents the governing property for estimating the durability of concrete structures. Permeation tests are non-destructive testing methods that measure the near-surface transport properties of concrete. The three categories of measuring concrete permeability are:

- hydraulic permeability which is the movement of water through concrete;
- gas permeability which is the movement of air through concrete;
- chloride-ion permeability which involves the movement of electric charge.

The measuring of chloride penetrability is the most commonly used non-destructive method that provides an indication of concrete permeability through established correlations. The standard guideline on the application and interpretation of chloride penetrability is ASTM C 1202: Standard Test Method for Electrical Indication of Concrete's Ability to Resist. The test involves coring a standard sized cylinder from the in-situ concrete. The sample is then trimmed, sealed with an epoxy coating from two sides, saturated in water and then placed in a split testing device filled with a sodium chloride solution with an applied voltage potential (Concrete Institute of Australia, 2008). The charge passing through the concrete is then measured where:

- a value of between 100 and 1000 Coulombs represents low permeability
- a value greater than 4000 Coulombs represents high permeability

2.8 *Ultrasonic pulse velocity method*

Ultrasonic pulse velocity methods involve propagating ultrasonic waves in solids while measuring the time taken for the waves to propagate between a sending and receiving point. The features of ultrasonic wave propagation can be used to characterize a material's composition, structure, elastic properties, density and geometry using previously established correlations, known patterns and mathematical relationships. This non-invasive technique is also used to detect and describe flaws in material as well as their severity of damage by observing the scattering of ultrasonic waves.

The basic technique of ultrasonic pulse velocity methods involve the transformation of a voltage pulse to an ultrasonic pulse and back by a transmitting and receiving transducer respectively. The transmitting transducer is placed onto the concrete surface and is allowed to transmit an ultrasonic pulse through the specimen medium. The ultrasonic pulse travels through the concrete specimen and is detected by a receiving transducer at the opposite end which transforms the ultrasonic pulse to a voltage pulse (Fig. 10). Knowing the distance between the two points, the velocity of the wave pulse can be determined. The velocity of the ultrasonic pulse provides a detailed account of the specimen under investigation. The following publications present standard guidelines for ultrasonic pulse velocity testing:

- ASTM C 597: Standard Test Method for Pulse Velocity Through Concrete;
- BS EN 12504-4:2004 Testing Concrete. Determination of Ultrasonic Pulse Velocity.

Figure 10. Ultrasonic pulse velocity test apparatus (Adapted from http://www.controls-group.com)

The factors contributing to the variability of ultrasonic pulse velocity methods as applied to concrete are aggregate properties, cement type, water-cement ratio, admixtures and age of concrete (Naik, Malhotra, & Popovics, 2004). Additionally, embedded reinforcement in the pulse path may have a significant effect on the measurements of pulse velocity (Concrete Institute of Australia, 2008). By taking these factors into account during analysis, ultrasonic pulse velocity methods are excellent means for investigating the uniformity and durability of concrete in a simple and inexpensive manner.

2.9 *Impact-echo method*

The impact-echo system is a recent development of ultrasonic methods which involves the measuring of concrete thickness and integrity using one surface. The test is also applied to determine the location of cracking, voids and delamination. It is based on monitoring the surface motion of concrete resulting from a short-duration mechanical impact. Specifically, the test measures the amplitude of reflected shock waves to detect flaws in concrete.

The impact-echo system uses an electro-mechanical transducer to generate a short pulse of ultrasonic stress waves that propagates into concrete plate-like structures. The different materials of different densities and elastic properties will reflect the stress pulse at their boundaries. The reflected pulse travels back to the transducer, which also acts as a receiver. An oscilloscope displays the received signal and the round trip travel time of the pulse is measured electronically. The distance of the reflecting interface can be determined by knowing the speed of the stress wave. The standard guideline on the application and interpretation of the impact-echo method is ASTM C 1383 -04: Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method.

The factors that affect the detection of a flaw within concrete are: the type of the flaw and its orientation, the depth of the flaw and the contact time of the impact (Carino N. , 2001). The impact-echo method proves to be a reliable method for locating a variety of defects in concrete structures. As with most methods for flaw detection in concrete, experience is required to interpret impact-echo test results.

2.10 *Corrosion of reinforcement method*

Corrosion of steel is an inevitable electrochemical and thermodynamical reaction which occurs spontaneously due to metallurgical characteristic of iron. Corrosion of steel reinforcement in concrete requires the loss of passivation, presence of moisture and/or the presence of oxygen. These conditions are often satisfied in concrete structures where corrosion can only be delayed or slowed down by preventative measures and techniques. The resulting iron oxides have unique chemical, electrical, magnetic and electrical properties which could be exploited in order to determine the extent of reinforcement corrosion by means of NDT.

Non-destructive methods of testing reinforcement corrosion require the use of a half-cell system and high-impedance voltmeters (Fig. 11). This system is capable of detecting the current flow of ion migration through the concrete between anodic and cathodic sites by measuring the resultant equipotential lines (Elsener, Müller, Suter, & Böhni, 1990). The concrete functions as an electrolyte and the risk of corrosion may be related empirically to the measured potential difference that leads to corrosion.

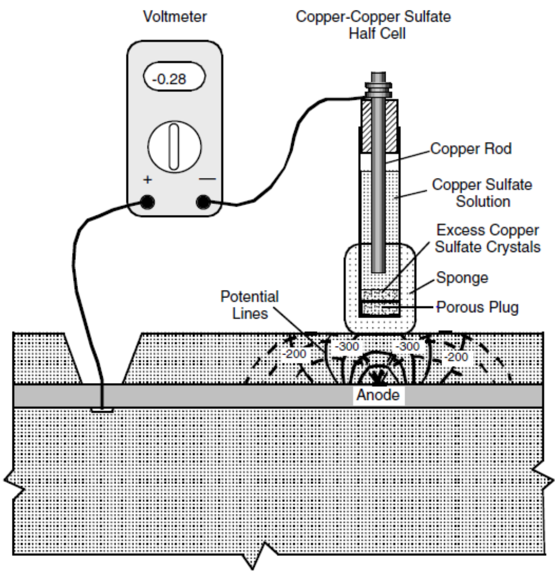

Figure 11. Schematic drawing of half-cell apparatus (Carino, 2004)

The standard guideline on application and interpretation of reinforcement corrosion testing is ASTM C 876 - 91: Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete. The conditions for the successful testing are exposure and electrical continuity of reinforcement in the test area. According to ASTM 876, there is a:

– 90% probability of active corrosion if negative potential is more than -350mV;
– 90% probability of no corrosion if negative potential is less than -200mV ;
– Uncertainty in corrosion if negative potential is between -350mV and -200mV.

The half-cell potential test is a useful technique to locate likely active areas of corrosion. It is recommended that potential surveys be supplemented with tests for carbonation and soluble chloride ion content for more accurate results.

3 FUTURE OF NON-DESTRUCTIVE TESTING

Advances in sensors, development of new materials, and miniaturization of devices are all paving the way for new NDT methods. Data fusion techniques are being developed to integrate several NDT methods in the aim of enabling effective data-acquisition, processing, and interpretation of test parameters in relation to material integrity. Much research interest and industry attention have been devoted to acoustic techniques of NDT. This is a result of a clear trend in testing concrete structures using acoustic signals processed by software using advanced data analysis algorithms.

NDT of concrete is increasingly gaining acceptance as a means of evaluating material integrity. Low awareness regarding NDT methods is hindering its uptake and is attributable to a lack of understanding construction materials and NDT methods themselves.

4 CONCLUSION

A wide range of non-destructive testing methods have been reviewed with reference to their potential, limitations, inspection techniques and interpretations. The factors that influence the success of NDT methods were explored and ways to mediate their influence were recommended. It was found that the majority of NDT methods rely on comparing tested parameters with established correlations. Empirical relationships provided by manufacturers were found to often provide unsatisfactory results. Where applicable, it is recommended to conduct test-specific correlation procedures for the NDT of concrete.

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