Strength assessment of in-situ concrete for the evaluation of structural capacity: State of the art

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ABSTRACT: With more emphasis on reusing and extending the life of structures, it often becomes necessary to assess the capacity of existing concrete structures. One major component of this assessment relates to the concrete strength. Most reliable results are obtained by taking cores. However, such assessment is ideally made with a combination of destructive and non-destructive testing to minimise damage to the structure. The currently available methods for assessing in-situ concrete strength of the existing structures can be broadly divided into two groups. One group of tests is completely non-destructive. The other group is partially destructive where limited damage to the surface is caused by the tests. For the strength evaluation of existing concrete, methods such as surface hardness test, ultrasonic pulse velocity test, penetration resistance test and maturity test fall under the non-destructive category. Partially destructive tests include pull out test, CAPO test, pull off test and break off test. This paper critically evaluates and analyses the applicability and limitations of the methods used for evaluating concrete strength in existing structures. Most methods for strength evaluation are found to measure a certain property such as elasticity, density, tensile strength or hardness of concrete and then relate the measured value to compressive strength. Studies on these methods show a wide variation in the correlations between estimated and predicted compressive strength. Partially destructive methods are noted to provide correlations with good consistency between estimated and predicted compressive strength.

KEY WORDS: Concrete; Compressive Strength; In-situ tests.

1 INTRODUCTION

Existing structures sometimes undergo structural modifications and changed loading condition with a view to reuse rather than demolishing and rebuilding. In these cases, assessment of the structure becomes necessary. Along with the information regarding the arrangement, orientation, dimension, and loading condition, properties of the materials used in the structures are required to be assessed for accurate evaluation of the existing structures.

Concrete is the most widely used construction material in the construction industry because of its ease of production, low cost, durability, and useful structural characteristics. Concrete is generally composed of aggregates, cement, and water. Properties of these constituting materials along with the mixing in different ratios affect the properties of concrete. Concrete properties are also affected by the variability of quality control in the production of concrete, its placement, consolidation, and curing. These result in the variation of concrete strength in the structure. Standard control samples prepared from the same concrete as in-situ may not reflect the strength of in-situ concrete. In-situ concrete strength is evaluated by destructive testing of cores collected from the structures. Core testing is time consuming and expensive and it may not be suitable in all cases because of difficult accessibility to the elements to be examined and risk of losing structural integrity. So, the number of cores that can be taken from the structures is limited. Several in-situ tests are used along with core test to minimize the number of cores to be undertaken and to reduce the uncertainty in compressive strength across a structure. In-situ tests have been developed based on the measurement of physical properties of concrete from which indirect measurement of concrete compressive strength can be inferred [1]. Among the in-situ tests, some are completely non-destructive while others are partially destructive which cause little surface damage without having effects on the structural integrity. Ultrasonic pulse velocity (UPV) test, rebound hammer test, maturity test, resonance frequency test etc. can be considered as non-destructive test. Tests such as pull out test, cut and pull out (CAPO) test, pull off test, break off test, penetration resistance test are partially destructive. For the sake of simplicity, all these in-situ tests are considered as non-destructive tests.

Historically, in-situ testing for concrete strength evaluation started with the surface hardness test. In the beginning of the twentieth century, the Brinell hardness testing for metal based on the indentation technique was adopted for evaluation of in-situ concrete strength by several researchers [2]. Skramtajew in 1938 reported 14 different techniques for the concrete strength estimation including pre-installed and post installed techniques [3]. Detailed historical evaluation of different in-situ tests can be found in the literature [2, 3, 5]. During recent years, much research has been devoted to the development and modification of the present in-situ tests, to gather information about the sensitivity of in-situ tests due to concrete variability, and to improve data processing technique for better strength assessment of concrete.

At present, standards and design manual and specifications suggests the requirement of calibration using core testing. The National Roads Authority in Ireland advises the use of in-situ tests after calibrating in-situ test results (usually by coring), as in-situ tests are not definitive and accuracy of in-situ test results is variable [5]. In-situ tests could be used to assist in determining the statistically most reliable results of core tests [6].

The paper addresses the in-situ tests that have been used for the strength estimation of concrete. The aim of the paper is to present the development, application and limitation of the mentioned in-situ tests on basis of previous research.

2 IN-SITU TEST: STRENGTH ESTIMATION OF CONCRETE

Previously stated in-situ tests measure some physical properties of concrete and relate the measured properties with the compressive strength of concrete. So, all these tests estimate the concrete compressive strength indirectly which leads to the uncertainty in the measurement of strength estimation. In-situ tests are discussed in the following sections. They are divided into two major groups, one is non-destructive test and another is partially destructive test.

2.1 Non-destructive tests

2.1.1 Rebound hammer test

Schimdt in 1948 introduced spring impact device of concrete by rebound principle [2]. The technique provides an easy measurement of rebound of impact hammer and the operation is quite simple. During the operation, a hammer mass impacts the concrete with a fixed energy and rebounds from the surface of the concrete after the impact. Energy of the hammer is applied by tensioning of spring and it is independent of the operator. Loss of energy during the impact of the hammer with concrete depends on the strength and elastic modulus of concrete. Since the introduction of the test, extensive research has been carried out to explain the interaction of the hammer with the concrete and energy dissipation in concrete, to figure out the sensitivity of the hammer under different influencing factors related to concrete and rebound hammer [6–14]. Akashi and Amasaki [16] investigated that wave propagation behaviour would be different for concrete having different strengths and boundary conditions of the contact between the hammer and the concrete. A good number of empirical relationships having different mathematical models for strength estimation can be found [10, 16, 17]. Szilagyi and Borosnyoi [11] suggested the use of rebound hammer within the respective domain of each model for the strength evaluation. Malhotra [14] reported ±15-20% deviation in strength assessment for control specimens prepared in the laboratory. Brencich et al. [8] assessed many factors including moisture content, stress state and maturity. Liu et al. [13] designed a model with nine parameters for strength estimation using rebound hammer. Many researchers argued about the existence of universal relationship of strength and rebound value [18]. In recent years, two different mathematical approaches [15, 17] have been suggested considering some factors such as measurement error, uncontrolled factors and model error. Szilagyi et al. [19] proposed a model (SBZ model) considering the surface hardness as a time dependent material property affected by water-cement ratio, carbonation and time. With all the limitations, this test is the most widely used for the strength estimation as it is easy, simple and inexpensive. The test method, the statistical characteristics of test results, the implementation of in-situ testing and interpretation of test results are described in ACI 228.1R-03, ASTM C805/C805M-12, EN 12504- 2:2012 and ISO 1920-7:2004 [18–21].

Rebound hammer provides an impact measurement at the point of interaction. It produces high variability being affected by numerous factors. The test can be used to assess the uniformity and quality of concrete in structure. The test should not be used for the basis of acceptance or rejection of concrete due to inherent uncertainty in concrete strength estimation.

2.1.2 Ultrasonic pulse velocity (UPV) test

Use of ultrasonic wave for defect detection in metal appeared in 1929. In 1940s, UPV test method was developed in Canada and England simultaneously [24]. The test method was developed on the basis of the propagation of mechanical wave through the material. For a homogeneous solid medium, the velocity of the ultrasonic wave depends on the elastic properties and density of the medium. The test method measures the time required for a wave to travel a particular distance from which velocity is measured. Several research and investigations were executed to understand the sensitivity of UPV test in concrete since the introduction of the test. In 1969, Jones and Facaoaru published the recommendation for testing concrete by UPV test [25]. Theoretical discussion can be found in details in [18, 20]. Kaplan [27] investigated the effect of age and water-cement ratio on the relationship of UPV and compressive strength of concrete. Ohdaira and Masuzawa [28] reported that high water content in the concrete results in higher velocity of the ultrasonic wave. Type and amount of aggregate significantly affect the UPV value in concrete [21, 26–28]. Ultrasonic pulse attenuation along with UPV was reported to be useful in estimation of concrete strength [32]. Bogas et al. [29] concluded that the relationship between UPV and compressive strength tends to be less affected by the aggregate volume in lightweight aggregate than normal weight aggregate. Solis-Carcano and Moreno [30] introduced a factor to define the aggregate property for better assessment of strength from UPV. Demirboga et al. [33] presented a general relationship of strength and UPV when assessing the effect of replacement of cement by different mineral admixtures. Type and amount of aggregate used for the research was constant. Presence of reinforcing bar in the concrete results in high error in UPV test as the velocity of wave is greater in steel than in concrete. Correction should be used if the reinforcement crosses the wave path. Turgut [34] suggested a universal relation between UPV and concrete strength. He considered laboratory specimens of different mix ratio and cores taken from the structures having different ages and unknown compositions. Popovics et al. discussed the difficulties of using UPV in concrete [35]. Komlos et al. [36] compared several standards of UPV test. He stated that the application of UPV test for strength estimation of concrete should be carried out with a suitable correlation curve.

Though with-in test variation has been found to be low [20], most reliable UPV test application is in concrete changes monitoring and mass uniformity checking [36]. The least recommended method of concrete strength estimation is the UPV test due to concrete inhomogeneity, material variability, and factors affecting the velocity of pulse.

2.1.3 Resonance frequency test

Resonance frequency method was first developed by Powers in 1938 and modified by Hornibrook in 1939 [37]. For a vibrating system of homogeneous, elastic and isotropic material, natural frequency of vibration is related to the dynamic modulus of elasticity and density [37]. The test works on the principle of resonating concrete specimen by applying excitations either by vibrating the specimen or by impacting with a small hammer. Resonance frequency tests have been performed for over 50 years and it has been mostly confined to laboratory based work as opposed to in-situ testing [37]. The high cost of the instrument, difficulty in data processing and portability result in low popularity of the test. The test is influenced by properties of aggregate and their mixing proportions, curing condition, and specimen size. The test is usually used in detecting deterioration of concrete rather than estimating strength. The test is not included in ACI 228 for in-situ strength estimation of concrete [20]. ASTM C215 suggests the use of the test in detecting changes in dynamic modulus of elasticity of concrete undergoing harsh environment [38]. Resonance frequency test is not commonly used for strength estimation of concrete. The test provides the means of studying the deterioration of concrete specimen subjected to aggressive environment.

2.1.4 Maturity test

Maturity method is a technique for estimating strength gain of concrete based on temperature history. The strength of concrete can be expressed as a function of time and temperature history which is related to the hydration process of cement paste of concrete. The origin of the method can be traced to a series of research related to the accelerated curing methods conducted during the late 1940s and early 1950s [39]. In 1951, Saul [40] presented a theory in defining maturity as the product of time and temperature. He stated that concrete of the same mix at the same maturity has approximately the same strength whatever combination of time and temperature make up that maturity [41]. The proposed maturity function to estimate the concrete strength was based on the assumption of linearity of strength gain and temperature and was able to predict the strength for limited range of curing temperatures. Several mathematical expressions for the maturity function were suggested to estimate the concrete strength reliably [38, 41]. Carino and Lew [41] reported that there is no single maturity function that is applicable to all concrete mixes. Procedures for using the maturity method have been standardized in ASTM C1074 [43]. Temperature history of concrete is a must for the maturity method. This method is applicable to new construction and early age strength development. The method can be used to determine in-situ strength of concrete to allow removal of formwork or shoring, opening of roadways to traffic etc. This is typically carried out with the help of pre-established empirical relationship of time-temperature and strength development

2.2 Partially destructive tests

2.2.1 Probe penetration test

Probe penetration test, considered as a hardness test [41, 42], measures the depth of penetration of probe into the concrete which provides the measure of hardness or penetration resistance. This can be related to concrete strength. Though the method was first introduced by Voellmy in 1954, its origin can be traced back to one of the method suggested by Skramtajaw in 1938 [2]. In 1964, a device, known as Windsor probe, was introduced in USA for the penetration testing of concrete to estimate the quality and strength. Later on Malhotra [46], Klotz [47], Arni [48] investigated the use of this test for compressive strength measurement. The test measures the compressibility of a localized area [44]. Aggregate hardness is taken to be the most influencing factor in the test results. The early age strength estimation of concrete has been reported to provide better accuracy compared to the rebound hammer test [49]. Manufacturer of the Windsor probe test system provides charts depending on the hardness of aggregate [44]. Several researchers indicated the correlations to be ineffective for strength estimation [cited in 22]. In 1980s, Windsor probe penetration test was modified to develop pin penetration test in which a smaller pin (in diameter and length) is forced into the concrete using a spring loaded device [44]. In recent years, nail penetration into the concrete by constant gas pressure has been studied [50]. Smaller sized nail with less energy than the Windsor probe penetration test is inserted into the concrete. Reliability of this nail penetration test has been reported to be higher than the rebound hammer, UPV and probe penetration test. The probe penetration test has been included in ASTM standard (ASTM C 803) in 1975 and the standard was modified to include the pin penetration test in 1990 [44].

Probe penetration test measures the compressibility of a small area. The test result produce high variability depending on the type of aggregates. Strength estimation is highly sensitive to the measured area. The test can be applicable to assess the uniformity of concrete.

2.2.2 Pull out test

Pull out test, also known as LOK test, measures the force required to extract an embedded metal insert from the concrete mass. The insert is pulled against a reaction force exerted on a concentric bearing ring placed around the insert. A conical shaped portion of concrete is extracted at the ultimate pull out load. Skramtajaw [3] first introduced the method which involved inserting a rod with a spherical end in the fresh concrete and then measuring the force needed to pull the rod from the hardened concrete. Later on in 1944, Tremper reported a non-linear relationship for the pull out force and compressive strength of concrete [51]. Both Skramtajaw and Tremper worked with the tensile strength of concrete because of the shape of the instrument they worked with. The present size and shape of the instrument is the result of the extensive study of Kierkegaard-Hansen carried out in the 1960s [51]. His work led to the introduction of bearing ring to fail the concrete along a predefined path. Many researchers studied the failure mechanism of concrete to explain the relationship between the pull out force and compressive strength [5, 48]. All these research concluded that pull out test subjects concrete to a non-uniform, three dimensional complex state of stress. Yener and Li [52] explained that relationship of concrete strength and pull out force could be attributed to the crushing of concrete. They performed plastic fracture finite element analysis to explain the failure mechanism. Krenchel and Shah [53] after the micro-cracking analysis, proposed with a two stage cracking process. A stable cracking begins at about 30% of peak load around the head of the insert inside the concrete and second stage that developed after the peak load defines the shape of cone. Krenchel and Bickley [cited in 28] explained the failure mechanism based on the progression of micro-cracking. They stated that pull out load and uniaxial compressive strength both undergo similar micro-cracking before failure. Despite lack of agreement on the failure mechanism, pull out load has good correlation with the compressive strength of concrete [20]. Pull out instrument is to be inserted in the fresh concrete which limits the test applicability. To overcome this limitation and to use in existing structures, various types of post installed instruments were investigated in the 1970s [54]. A post installed method known as CAPO test having the same geometry as pull out test was developed by Petersen in 1976 [55]. The concrete is subjected to same type of loading as pull out test and the failure mechanism resembles the pull out test [51]. Petersen investigated several correlations proposed by researchers between pull out force and strength of concrete for both pull out and CAPO tests [55]. He reported identical correlation for the two tests. Petersen and Poulsen [56] suggested two general correlations for the strength estimation of normal concrete, one is for low strength region and another is for high strength region. For lightweight concrete, Krenchel and Nasser [cited in 32] suggested different correlations. Pull out test along with CAPO test as post installed pull out test has been included in different standards including ASTM C900 and EN 12504-part 3 [19,55]. In recent years, a new pull out technique (B15G insert) has been presented [57, 58]. Brecncich [59] described the operation of the technique with respect to pull out/ CAPO test.

Pull out and CAPO test provide direct measurement of static loading subjected to concrete. Variability in strength estimation depends on the aggregate type. There exists a strong relationship between the compressive strength of concrete and pull out strength [20]. The application of the tests is in high reliable estimation of concrete compressive strength [60].

2.2.3 Break off test

Break off test was introduced by Johansen in 1976 in Norway. The test is based on the measurement of the flexural tensile strength parameter of concrete which can be indirectly related to compressive strength. The test measures the force required to break off a cylindrical core from a larger concrete mass. The test specimen can be prepared by inserting a tubular plastic sleeve during concrete casting or by drilling the hardened concrete at the time of testing. Load configuration is the same as the cantilever beam with circular cross section subjected to a concentrated load at its free end [61]. The test method creates a state of combination of bending and shear stress at the base of the cylindrical core [4]. A good number of research was carried out in the 1980s [61]. Nishikawa [62] reported impractical relationship between break off test result and compressive strength of concrete. Break off test was found be sensitive to the water-cement ratio, age of concrete, curing and cement type. Naik et al. [63] found the influence of type of aggregate and specimen on the break off test results. Crushed aggregate resulted in higher test results than the rounded aggregate. However, while studying the performance of break off test in high strength concrete, Naik and Salameh [64] found the influence of type of aggregate and test specimen (preinstalled or post-installed) to be negligible. Size of aggregate has high influence on the variability of the test results [20]. ASTM included the test in 1990 as ASTM C 1150 and withdrew the test in 2002 [61].

Break off test is not commonly used in recent years. The test provides an indirect estimation of compressive strength. The test results highly variable. The test is suitable for near surface flexural tensile strength measurement of concrete.

2.2.4 Pull off test

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 concrete. The test was developed in 1970s in United Kingdom [65]. Similar test was developed in Austria (tear off test) and Denmark (007-Bond test) [2, 64]. The test is a direct tension test of concrete. With the pre-established correlation, compressive strength of a particular concrete is measured from the pull off test results. Aggregate type has high influence in the test results [65]. The test is included in ASTM C1583 [66]. BS 1881-207 reported 15% variation under laboratory condition in strength estimation [67]. ASTM C 1583 limits the use of the test for estimation of tensile strength of concrete surface and bond strength of overlay material [68].

Pull off test measures the compressive strength of concrete indirectly. The test is particularly suitable for testing near surface tensile strength of concrete. This test is not recommended for the estimation of concrete compressive strength.

2.3 Combination of in-situ tests

Combination of several in-situ tests has been reported in 1960s for the purpose of improving the reliability and precision in concrete strength estimation [69]. The concept behind the development of combining in-situ tests is that if two test methods are influenced in two different ways by the same factor, their combined use results in a cancelling effect which improves the strength estimation [2]. Among the various suggested combinations, use of combination of UPV and rebound hammer (known as SonReb method) is the most common practice. Different mathematical models has been proposed by researchers. Researchers reported better correlations while using the combined methods for strength estimation [62–68]. Many researchers proposed universal relations for the strength estimations [67, 69]. Qasrawi [75] proposed a nomograph where concrete strength was expressed as a function of two variable. Nomograph consisted of different contours of rebound hammer value having concrete strength along one axis, UPV test result along other axis. Arioĝlu [77] suggested similar nomograph having UPV test result as the contour line. Several other combinations of in-situ have been reported in recent years including the use of Windsor probe penetration test and resonance frequency test with SonReb method [64, 66]. Breysse [18] explained that combination may not always lead to better correlation. When one test provides much poorer results than the other, combination will not result in increased accuracy for strength estimation.

2.4 Comparative assessment

Several researchers reported comparative assessment of estimating concrete strength using different in-situ test methods. Arni [48] compared the rebound hammer and probe penetration test for strength estimation. He concluded that neither of the tests should be used for strength estimation. For quality assessment, rebound hammer could be used ahead of probe penetration because of its low cost, less destructive nature, and ability to provide greater number of test data. Yun et al. [78] reported the comparison of several NDTs. The work of Qasrawi [75] indicated that UPV test showed more accuracy than rebound hammer in strength prediction. Shariati [76] found rebound hammer test to be more accurate than UPV test in strength prediction. Pascale et al. [79] showed limitation of probe penetration test in estimating strength of high strength concrete.

3 CONCLUSION

Several in-situ test methods have been reviewed in this paper based on previous research results. All in-situ tests are suggested to be used for strength estimation within their limitations. Correlation of strength and in-situ test result for the concrete to be investigated should be prepared beforehand. Rebound hammer and penetration resistance test provide information of surface properties. Break off test measures flexural property while pull off test provides tensile strength property of concrete. UPV and resonance frequency test provide inside properties of concrete. Pull out test and CAPO test provide strong relationship with the compressive strength. Efficiency and quality of strength estimation depend on the sensitivity of strength to the in-situ tests, measurement error and range of variation of in-situ test results as compared to the variation of strength. Combination of two or more in-situ tests can be helpful in that context.

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REFERENCES

[1] V. M. Malhotra and Carino N. J., *Handbook on Non Destructive Testing of Concrete*, 2nd ed. Boca Raton, USA: CRC Press, 2004.

[2] N. J. Carino, "Nondestructive Testing of Concrete - History and Challenges," in *Concrete Technology- Past, Present and Future*, 1994, pp. 623–678.

[3] B. G. Skramtajew, "Determining Concrete strength For Control Of Concrete In Structures," *Journal Proceedings*, vol. 34, no. 1, pp. 285–304, Jan. 1938.

[4] N. J. Carino, "Nondestructive test methods," in *Concrete Construction Engineering Handbook*, 2nd ed., Edward G. Nawy, Ed. Boca Raton, USA: CRC press, 2008, pp. 1–74.

[5] "NRA BA 86 Advice Notes on the Non-Destructive Testing of Road Structures," *National Roads Authority*, vol. 3, 2014.

[6] L. Jacinto, L. O. Santos, and L. C. Neves, "Bayesian probabilistic assessment of in-situ concrete strength," *Large Structures and Infrastructures for Environmentally Constrained and Urbanised Areas*, pp. 228–229, 2010.

[7] A. Basu and A. Aydin, "A method for normalization of Schmidt hammer rebound values," *International Journal of Rock Mechanics & Mining Sciences*, vol. 41, pp. 1211–1214, 2004.

[8] A. Brencich, G. Cassini, D. Pera, and G. Riotto, "Calibration and Reliability of the Rebound (Schmidt) Hammer Test," *Civil Engineering and Architecture*, vol. 1, no. 3, pp. 66–78, 2013.

[9] G. W. Greene, "Test Hammer Provides New Method of Evaluating Hardened Concrete," *Journal Proceedings*, vol. 51, no. 11, pp. 249–256, Nov. 1954.

[10] S. Hannachi and M. N. Guetteche, "Review of the Rebound Hammer Method Estimating Concrete Compressive Strength on Site," in *International Conference on Architecture and Civil Engineering* , 2014, pp. 118–127.

[11] K. Szilágyi and A. Borosnyói, "50 Years of Experience With the Schmidt," *Concrete Structures*, vol. 10, pp. 46–56, 2009.

[12] E. Kolaiti and Z. Papadopoulos, "Evaluation of Schmidt Rebound Hammer Testing : a Critical Approach," *Bulletin of the International Association of Engineering Geology*, vol. 48, no. 1985, pp. 69–76, 1993.

[13] J. C. Liu, M. L. Sue, and C. H. Kou, "Estimating the strength of concrete using surface rebound value and design parameters of concrete material," *Tamkang Journal of Science and Engineering*, vol. 12, no. 1, pp. 1–7, 2009.

[14] V. M. Malhotra, "Surface Hardness Method," in *Handbook on Non Destructive Testing of Concrete*, 2nd ed., V. M. Malhotra and J. N. Carino, Eds. Boca Raton, USA: CRC Press, 2004, pp. 1–1–1–16.

[15] K. Szilágyi, "Rebound surface hardness and related properties of concete," Budapest Unniversity of Technology and Economics, 2013.

[16] T. Akashi and S. Amasaki, "Study of the Stress Waves in the Plunger of a Rebound Hammer at the Time of Impact," *Special Publication, American Concrete Institute*, vol. 82, pp. 17–34, Sep. 1984.

[17] D. Breysse and J. L. Martínez-Fernández, "Assessing concrete strength with rebound hammer: review of key issues and ideas for more reliable conclusions," *Materials and Structures*, vol. 47, no. 9, pp. 1589–1604, 2013.

[18] D. Breysse, "Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods," *Construction and Building Materials*, vol. 33, pp. 139–163, 2012.

[19] K. Szilágyi, A. Borosnyói, and I. Zsigovics, "Rebound surface hardness of concrete: Introduction of an empirical constitutive model," *Construction and Building Materials*, vol. 25, no. 5, pp. 2480–2487, 2011.

[20] ACI Committee Report 228.1R, "In-Place Methods to Estimate Concrete Strength Reported," 2003.

[21] ASTM C805 / C805M - 13a, " Standard Test Method for Rebound Number of Hardened Concrete," 2014.

[22] EN 12504-2:2012, "Testing concrete in structures. Non-destructive testing. Determination of rebound number," 2013.

[23] ISO 1920-7:2004, " Testing of concrete - Part 7: Non-destructive tests on hardened concrete," 2004.

[24] T. R. Naik, V. M. Malhotra, and J. S. Popovics, "The Ultrasonic Pulse Velocity Method," in *Handbook on Nondestructive Tesitng of Concrete*, 2nd ed., no. Civil, V. M. Malhotra and N. J. Carino, Eds. Boca Raton, USA: CRC Press, 2004, pp. 8–1–8–19.

[25] R. Jones and I. Fąçąoaru, "Recommendations for testing concrete by the ultrasonic pulse method," *Matériaux et Constructions*, vol. 2, no. 4, pp. 275–284, 1969.

[26] J. H. Bungey, S. G. Millard, and M. G. Grantham, "The ultrasonic pulse velocity method," in *Testing of Concrete in Strucures*, 4th ed., Abingdon, England: Taylor & Francis, 2006, pp. 51–81.

[27] M. F. Kaplan, "The effects of age and water/cement ratio upon the relation between ultrasonic pulse velocity and compressive strength of concrete," *Magazine of Concrete Research*, vol. 11, no. 32, pp. 85–92, Jul. 1959.

[28] E. Ohdaira and N. Masuzawa, "Water content and its effect on ultrasound propagation in concrete--the possibility of NDE," *Ultrasonics*, vol. 38, pp. 546–552, 2000.

[29] J. A. Bogas, M. G. Gomes, and A. Gomes, "Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method," *Ultrasonics*, vol. 53, no. 5, pp. 962–972, 2013.

[30] R. Solis-Carcano and E. I. Moreno, "Evaluation of concrete made with crushed limestone aggregate based on ultrasonic pulse velocity," *Construction and Building Materials*, vol. 22, no. 6, pp. 1225–1231, 2008.

[31] H. Tanyidizi and A. Coskun, "Determination of the principal parameter of ultrasonic pulse velocity and compressive strength of lightweight concrete by using variance method," *Russian Journal of Nondestructive Testing*, vol. 44, no. 9, pp. 639–646, 2008.

[32] M. T. Liang and J. Wu, "Theoretical elucidation on the empirical formulae for the ultrasonic testing method for concrete structures," *Cement and Concrete Research*, vol. 32, no. 11, pp. 1763–1769, 2002.

[33] R. Demirboğa, I. Türkmen, and M. B. Karakoç, “Relationship between ultrasonic velocity and compressive strength for high-volume mineral-admixtured concrete,” *Cement and Concrete Research*, vol. 34, no. 12, pp. 2329–2336, 2004.

[34] P. Turgut, “Research into the correlation between concrete strength and UPV values,” *NDT.net*, vol. 12, no. 12, pp. 1–9, 2004.

[35] S. Popovics, J. L. Rose, and J. S. Popovics, “The behavior of ultrasonic pulses in Concrete,” *Cement and Concrete Research*, vol. 20, no. 2, p. Pages 259–270, 1990.

[36] K. Komloš, S. Popovics, T. Nürnbergerová, B. Babál, and J. S. Popovics, “Ultrasonic pulse velocity test of concrete properties as specified in various standards,” *Cement and Concrete Composites*, vol. 18, no. 5, pp. 357–364, 1996.

[37] V. M. Malhotra and V. Sivasundaram, “Resonant Frequency Methods,” in *Handbook on Non Destructive Testing of Concrete*, 2nd ed., Boca Raton, USA: CRC press, 2004, pp. 7–1–7–21.

[38] ASTM C 215 - 14, “Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens,” 2014.

[39] N. J. Carino, “The Maturity Method,” in *Handbook on Non Destructive Testing of Concrete*, 2nd ed., V. M. Malhotra and N. J. Carino, Eds. Boca Raton, USA: CRC Press, 2004, pp. 5–1–5–47.

[40] A. G. A. Saul, “Principles underlying the steam curing of concrete at atmospheric pressure,” *Magazine of Concrete Research*, vol. 2, no. 6, pp. 127–140, Mar. 1951.

[41] N. Carino and H. Lew, “The maturity method: from theory to application,” *Structures Congress and Exposition 2001*, pp. 1–19, 2001.

[42] T. Naik, “Maturity of concrete: Its applications and limitations,” *Advances in Concrete Technology, CANMET, 1992, Canada*.

[43] ASTM C1074-11, “ Standard Practice for Estimating Concrete Strength by the Maturity Method,” 2011.

[44] V. M. Malhotra and Carette G.G., “Penetration Resistance Method,” in *Handbook on Non Destructive Testing of Concrete*, 2nd ed., vol. 2, V. M. Malhotra and Carino N. J., Eds. Boa Raton, USA: CRC Press, 2004, pp. 2–1–2–18.

[45] J. F. Lamond, *Significance of Tests and Properties of Concrete and Concrete-making Materials, Issue 169, Part 4*. ASTM International, 2006.

[46] V. M. Malhotra, “Evaluation of the windsor probe test for estimating compressive strength of concrete,” *RILEM Materials and Structures*, vol. 7, no. 37, pp. 3–15, 1974.

[47] R. C. Klotz, “Field investigation of concrete quality using the windsor probe test system,” *Highway Research Record*, no. 378, 1972.

[48] H. T. Arni, “Impact and penetration tests of tests of portland cement concrete,” *Highway Research Record*, no. 378, 1972.

[49] G. G. Carette and V. M. Malhotra, “In Situ Tests: Variability and Strength Prediction of Concrete at Early Ages,” *Special Publication*, vol. 82, pp. 111–142, Sep. 1984.

[50] L. Selcuk, H. S. Gokce, K. Kayabali, and O. Simsek, “A Nondestructive Testing Technique: Nail Penetration Test,” *ACI Structural Journal*, vol. 109, no. 2, pp. 245–252, 2012.

[51] N. J. Caniro, “Pull out test,” in *Handbook on Non Destructive Testing of Concrete*, 2nd ed., N. J. Malhotra, V. M. and Carino, Ed. Boca Raton, USA: CRC Press, 2004, pp. 3–1–3–40.

[52] M. Yener and G. C. Li, “Progressive Finite Element Fracture Anlysis of Pullout Concrete,” *Journal of Structural Engineering*, vol. 117, no. 8, pp. 2351–2371, 1991.

[53] H. Krenchel and S. P. Shah, “Fracture analysis of the pullout test,” *Materials and Structures*, vol. 18, no. 6, pp. 439–446, Nov. 1985.

[54] J. H. Bungey, S. G. Millard, and M. G. Grantham, *Testing of Concrete in Strucures*, 4th ed. Abingdon, England: Taylor & Francis, 2006.

[55] C. G. Petersen, “LOK-TEST and CAPO-TEST pullout testing, twenty years experience,” in *Non-Destructive Testing in Civil Engineering Conference*, 1997.

[56] C. G. Petersen and E. Poulsen, “Pullout testing by LOK-test and CAPO-test with particular reference to the in-place concrete of the Great Belt Link,” Dansk Betoninstitut A/S, Virum, Denmark., 1992.

[57] EN 12504-3:2005, “Testing concrete in structures. Determination of pull-out force,” 2005.

[58] F. L. Bovio, G. L. Bovio, A. Brencich, G. Cassini, D. Pera, and G. Riotto, “A New Pull-Out Technique for In-Place Estimation of Concrete Compressive Strength,” *Advances in Materials Science and Engineering*, vol. 2014, p. 8, 2014.

[59] A. Brencich, “A post-installed insert for pull-out tests on concrete up to 70MPa,” *Construction and Building Materials*, vol. 95, pp. 788–801, 2015.

[60] ASTM C 900 - 15, “Standard Test Method for Pullout Strength of Hardened Concrete,” 2015.

[61] T. R. Naik, “The Break-off Test Method,” in *Handbook on Nondestructive Testing of Concrete*, 2nd ed., N. J. C. V. M. Malhotra, Ed. Boa Raton, USA: CRC Press, 2004, pp. 1–16.

[62] A. S. Nishikawa, “A Nondestrucitve Testing Procedure for In-Place Evaluation of Flexural Strength of concrete: Informational Report. Joint Highway Research Project, Indiana Department of Transportation and Purdue University, Indiana,” 1983.

[63] T. Naik, Z. Salameh, and A. Hassaballah, “Evaluation of In-Place Strength of Concrete By The Break-Off Method,” in *Preceedings of the NDT&E for Manufacturing and Construction Conference*, 1988, p. 54.

[64] T. R. Naik and Z. Salameh, “Evaluation of high strength concrete by the break-off method,” in *First Materails Engineering Congress*, 1990, vol. 2.

[65] G. D. Henderson, P. A. M. Basheer, and A. E. Long, “Pull-off test and permeation tests,” in *Handbook on non-detructive tesing on concrete*, 2nd ed., V. M. Malhotra and N. J. Carino, Eds. Boca Raton, USA: CRC Press, 2004, pp. 6–1–6–12.

[66] ASTM C1583 / C1583M - 13, “Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method),” *2013*.

[67] BS 1881-207:1992, “Testing concrete. Recommendations for the assessment of concrete strength by near-to-surface tests,” 1992.

[68] ASTM C 1583/ C 1583M - 13, “Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method),” 2013.

[69] A. Samarin, “Combined Methods,” in *Handbook on Non Destructive Testing of Concrete*, 2nd ed., V. M. Malhotra and N. J. Carino, Eds. Boca Raton, 2004, pp. 9–1–9–12.

[70] M. Erdal, “Prediction of the Compressive Strength of Vacuum Processed Concretes Using Artificial Neural Network and Regression Techniques,” *Scientific Research and Essays*, vol. 4, no. 10, pp. 1057–1065, 2009.

[71] B. Hobbs and M. T. Kebir, “Non-destructive testing techniques for the forensic engineering investigation of reinforced concrete buildings,” *Forensic Science International*, vol. 167, no. 2–3, pp. 167–172, 2007.

[72] W. Martinez-Molina, A. A. Torres-Acosta, J. C. Jauregui, H. L. Chavez-Garcia, E. M. Alonso-Guzman, M. Graff, and J. C. Arteaga-Arcos, “Predicting concrete compressive strength and modulus of rupture using different NDT techniques,” *Advances in Materials Science and Engineering*, vol. 2014, 2014.

[73] L. Nobile, “Prediction of concrete compressive strength by combined non-destructive methods,” *Meccanica*, vol. 50, no. 2, pp. 411–417, 2015.

[74] R. Pucinotti, “The use of multiple combined non destructive testing in the concrete strength assessment,” *HSNDT International 2007 on ndt.net*, pp. 1–7, 2007.

[75] H. Y. Qasrawi, “Concrete strength by combined nondestructive methods simply and reliably predicted,” *Cement and Concrete Research*, vol. 30, no. 5, pp. 739–746, 2000.

[76] M. Shariati, N. H. Ramli-Sulong, M. M. Arabnejad, P. Shafigh, and H. Sinaei, “Assessing the strength of reinforced concrete structures through Ultrasonic Pulse Velocity and Schmidt Rebound Hammer tests,” *Scientific Research and Essays*, vol. 6, no. 1, pp. 213–220, 2011.

[77] E. Arioĝlu, N. Ariôlu, and C. Girgin, “A discussion of the paper ‘concrete strength by combined nondestructive methods simply and reliably predicted’ by H.Y. Qasrawi,” *Cement and Concrete Research*, vol. 31, no. 8, pp. 1239–1240, 2001.

[78] C. H. Yun, K. R. Choi, S. Y. Kim, and Y. C. Song, “Comparative Evaluation of Nondestructive Test Methods for in-Place Strength Determination,” *Special Publication*, vol. 112, pp. 111–136, Jan. 1989.

[79] G. Pascale, A. Di Leo, and V. Bonora, “Nondestructive Assessment of the Actual Compressive Strength of High-Strength Concrete,” *Journal of Materials in Civil Engineering, ASCE*, vol. 15, no. 5, pp. 452–459, 2003.