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Narrative Review on Non-Destructive Testing of Concrete

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***Abstract*—This paper audits the most widely recognized non-ruinous testing (NDT) strategies for concrete structures as used by the auxiliary designing industry. The essentials of NDT strategies are investigated with respect to their latent capacity, restrictions, assessment methods, and understandings. The elements that impact the achievement of NDT strategies are examined and approaches to intervene their impact are suggested. Reference is made to standard rules for the application and understanding of the talked about NDT techniques. NDT of concrete was increasing expanding acknowledgment as methods for assessing the quality, consistency, sturdiness, and different properties of existing concrete structures. View of NDT insufficiency was owing to an absence of comprehension of construction materials and NDT techniques themselves. The aim of this paper is to address these worries by recognizing and depicting the most widely recognized fruitful strategies for NDT as applied to concrete structures.**

***Index Terms*— Concrete; Construction; Non-destructive testing; Review.**

I. INTRODUCTION

Non-destructive testing (NDT) is characterized as the course of investigating, testing, or assessing materials, segments, or congregations without annihilating the functionality of the part or framework [1, 2]. The reason for NDT is to decide the quality and honesty of materials, segments, or congregations without influencing the capacity to play out their planned capacities. The non-ruinous tendency should not be mistaken for non-intrusiveness. Testing techniques that don't influence the future value of a section or framework are viewed as non-damaging regardless of whether they comprise of obtrusive activities [2, 3]. For instance, coring is a typical NDT strategy that is utilized to concentrate and test examples from concrete parts so as to decide the properties of in-situ concrete. Coring modifies the presence of the segment and imperceptibly influences its basic trustworthiness. Whenever done effectively, coring keeps up the usefulness of the auxiliary part and is in this way viewed as non-dangerous. Damaging testing investigates disappointment components to decide the mechanical properties of the material, for example, yield quality, compressive quality, rigidity, malleability, and break durability. NDT techniques investigate signs of properties without arriving at part or get together disappointments. Broad endeavors and headways have been made to create NDT strategies fit for showing mechanical, acoustical, concoction, electrical, attractive, and physical properties of materials. One of the most punctual archived endeavors of NDT dates to the nineteenth century where breaks were recognized in railroad

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wheels by methods for acoustic tap testing [3, 4]. Increasingly delicate, solid, and quantifiable NDT techniques have expansively developed lately. NDT strategies have appeared as a reaction to the requirement for auxiliary harm identification and anticipation. The broad utilization of NDT is driven by financial aspects and security. In a pre-emptive endeavor to annihilate the issues related to basic disintegration, novel in-site testing methods have been created to consider the evaluation of concrete during the construction, authorizing, and overhauling lifecycle phases of a structure. The central point that impacts the achievement of a non-ruinous review is the profundity of the entrance, vertical and horizontal goals, the complexity in physical properties, signal-to-clamor proportion, and existing data about the structure [4-6]. The comprehension of material properties and the key issues related to their application in auxiliary designing is basic for the accomplishment of any NDT technique. The means of picking a sufficient NDT strategy are [7, 8]:

- Understanding the physical idea of the material property or irregularity to be assessed.
- Understanding the hidden physical procedures that administer the NDT technique.
- Understanding the physical idea of the association of the examining field with the test material
- Understanding the possible confinements of accessible NDT innovation.
- Thinking about financial, natural, administrative, and different elements.

There is a wide scope of NDT techniques that are utilized by the common and basic designing industry. While there gives off an impression of being plentiful specialized writing with respect to NDT of concrete, there is an absence of joint effort between structural designers, NDT analysts, and authorities. The goal of this paper is to overcome any issues by recognizing and depicting the most widely recognized techniques for NDT as applied to concrete structures. Table 1 shows some of the general factors to be considered during NDT testing of RCC.

TABLE I. NON-DESTRUCTIVE TESTING TECHNIQUES FOR RCC STRUCTURE DESIGN

Testing Techniques	**Factors to be considered for RCC structure and materials design**
Visual inspection	Macroscopic faults, deformation, cracks, etc.
Acoustic techniques Ultrasonic pulse-velocity Acoustic emission Echo-impact technique	Modulus of elasticity, minor flaws, corrosion rate, hardness, etc.
Physical techniques Rebound hammer technique Flat Jack hammer	Hardness, compressive strength, etc.
RADAR based techniques Ground penetration radar	Moisture content, cracks, location of the rebar, concrete depth, etc.
Penetrating radiation methods Radiometry Radiography	Defects in the material sub-surface, concrete voids, and quality
Characterization X-ray diffraction X-ray tomography	Reason behind corrosion, corrosion, volume of corrosion related to chemical reactions
Thermal imaging Infra-red thermography	Temperature of concrete surfaces, depth of cracks and their types, etc.
Corrosion diagnosis tests Chloride penetration test Half-cell potential test Volhard test Quantab Test	Depth of carbonation, ingress rate of chloride, corrosion rate, etc.

II. NDT TESTING PROCEDURES

A. Surface hardness based methods

Non-destructive surface hardness techniques are non-intrusive systems that research the quality attributes of the material. The two classifications that characterize concrete surface hardness procedures are space strategies and rebound techniques. These techniques endeavor to abuse experimental connections between quality properties of concrete and surface hardness as estimated by space or rebound. Starting in the 1930 [12], space techniques are

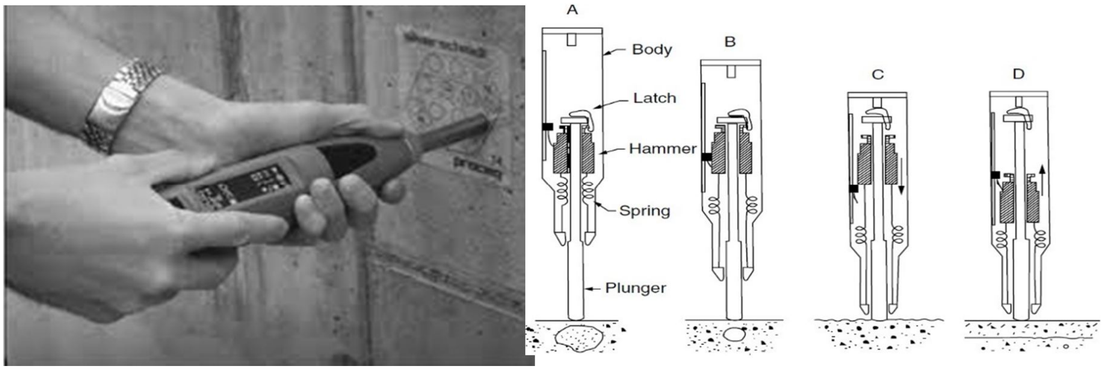

Fig. 1. (a) Schmidt rebound hammer used for NDT in concrete; (b) Procedure of the rebound hammer. [7, 8]

not, at this point basic in the structural building industry, though rebound strategies are every now and again applied to explore concrete quality attributes concerning standard rules on testing and translation. The most ordinarily utilized surface hardness methodology is the standard rebound hammer test. The test was created in 1948 by Swiss designer Ernst Schmidt and is regularly alluded to as the Schmidt Rebound Hammer [13-15]. Upon sway with the concrete surface, the rebounded hammer records a rebound number which presents a sign of solidarity properties by referencing built up experimental connections between quality properties of concrete (compressive and flexural) and the rebound number. The basic comprehension of the effect and rebound identifies with the hypothesis of wave engendering. A pressure wave is proliferated when the surface of the concrete is upset by the unclogged (σ_i). The response power engenders a reflected pressure wave through the unclogged (σ_r). The proportion of the wave amplitudes (σ_r/σ_i) is seen as relative to the rebound number which could be observationally associated to compressive and flexural quality [16-18]. The activity of the Standard Rebound Hammer requires fewer mechanical abilities when contrasted with different techniques for NDT. A visual assessment of the concrete surface ought to be directed preceding the test to distinguish a smooth surface reasonable for testing. The test can be led in any directional edge where alignment outlines are utilized to moderate the various impacts of gravity (Fig. 1a). The hammer is squeezed against the concrete surface until a spring-stacked mass is discharged making the unclogged sway against the surface and rebound a separated estimated by a sliding marker (Fig. 1b). The deliberate separation is alluded to as the rebound number. Experimental relationships are given by the producer to relate the rebound number to concrete quality properties; be that as it may, the testing states of the maker may be unlike the conditions present. In this way, it is prescribed to lead a test-explicit relationship strategy where several concrete chambers extending in quality are arranged and tried by both Standard Rebound Hammer and compression-testing machine. The consequences of the two tests are then coordinated into a basic relapse examination model which yields an experimental relationship by methods for conventional least squares. The accompanying distributions present standard rules for the application and understanding that administer 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 gives a basic, simple, and modest strategy to gauge concrete quality properties. Notwithstanding, the consequences of the test on concrete are influenced by different factors, for example, perfection of the surface, geometric properties of the test example, age of the test example, surface and inside dampness states of the concrete, sort of coarse total, kind of concrete, kind of form and carbonation of the concrete surface (Malhotra, 2004). Quality estimation from rebound readings of examples like connection bend examples is accomplished inside a precision of 15% to 20% (Concrete Institute of Australia, 2008). It is in this way suggested the standard rebound hammer test be utilized as a strategy for testing fluctuation of solidarity properties between concrete examples as opposed to as a substitute for standard compression testing.

B. Penetration resistance based methods

Penetration resistance strategies are obtrusive NDT methodology that investigates the quality properties of concrete utilizing recently settled relationships. These techniques include driving tests into concrete examples utilizing a uniform power. Estimating the test's profundity of infiltration gives a sign of concrete compressive quality by alluding to relationships. Because of the inconsequential impact of the infiltration opposition strategies on the auxiliary uprightness of the examined test, the tests are viewed as non-destructive in spite of the unsettling influence of the concrete during the entrance. The most normally utilized infiltration opposition strategy is the Windsor test framework. The framework comprises of a powder-activated weapon, which drives hardened permit steel tests into concrete examples while estimating entrance separation by means of a profundity measure (Fig. 2a). The accompanying distributions present standard rules for the application and translation that oversee entrance testing:

- ASTM C 803-02: Standard Test Method for Penetration Resistance of Hardened Concrete.
- BS 1881-207 Testing Concrete - Recommendations for the evaluations of concrete quality by close to-surface tests.

The entrance of the Windsor test makes dynamic anxieties that lead to the devastating and breaking of the close surface concrete (Fig. 2b). A cone-molded zone creates upon entrance, which includes breaking and is opposed by the compression of the adjoining concrete. The obstruction is experimentally associated to test entrance profundity; be that as it may, exact connections gave by producers frequently yield unacceptable outcomes. There-front, test-explicit connection techniques ought to be directed using entrance strategies and compression-testing machines to accomplish progressively exact relationship graphs.

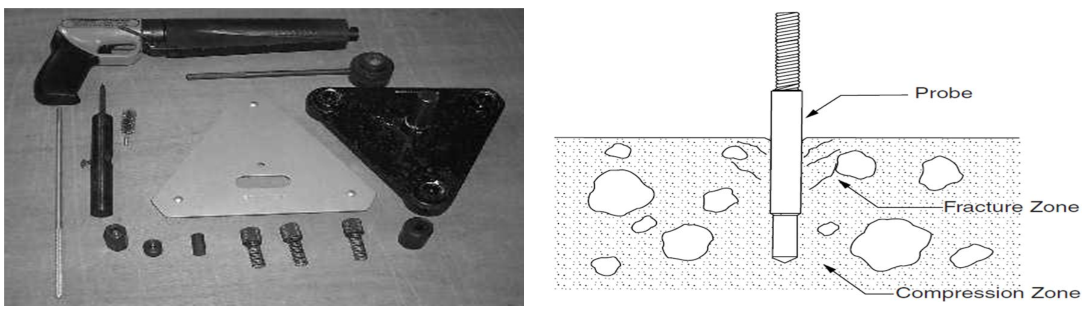

Fig. 2. (a) Components of the Windsor Probe System; (b) Diagram of typical concrete failure mechanism during probe penetration [8, 9]

The components that add to the inside test variability are inferable from administrator blunder, hardware mistake, size of totals, and the heterogeneous idea of concrete [8, 9]. The most critical factor that effects inside test variability is total size. For instance, a 5% coefficient of variety is normal for testing tests of 20mm total size; though, a 14% coefficient of variety is normal for tests of 55mm total size [9]. All things considered, varieties in the assessed early quality of concrete are low to direct, which gives a sensible level of precision and sureness for the evacuation of formwork in concrete constructions. Furthermore, the number of variables adding to inside test variability is less than those of other NDT systems, for example, surface hardness techniques. The Windsor probe system is fast, modest, and easy to work. Similarly, as with surface hardness techniques, the entrance opposition strategies do not yield total estimations of solidarity and must, along these lines, be utilized as a strategy for testing variability of solidarity properties between concrete examples.

C. Pull-out resistance methods

Pull-out opposition techniques measure the power required to extricate standard installed embeds from the concrete surface. Utilizing built up connections, the power required to expel the supplements gives a gauge of concrete quality properties. The two kinds of supplements, cast-in, and fixed set up, characterize the two sorts of pull-out strategies. Cast-in tests require a supplement to be situated inside the new concrete before its arrangement. Fixed set up tests require less premonition and include situating a supplement into a penetrated opening inside hardened concrete. Pull-out obstruction techniques are non-destructive yet obtrusive strategies that are usually used to appraise compressive quality properties of concrete. The most regularly utilized draw out test strategy is the LOK test created in 1962 by Kierkegaard-Hansen [13, 14]. The test requires a supplement insertion of 25mm to guarantee adequate testing of concrete with coarse totals (Fig. 3). The power required to expel the addition is alluded to as the "low-quality", which in another draw out opposition strategies is alluded to as the draw out power.

The accompanying distributions present standard rules for pull-out opposition testing

- ASTM Standard C 900-13a: Standard Test Method for Pull-out Strength of Hardened Concrete
- BS 1881-207 Testing Concrete - Recommendations for the evaluations of concrete quality by close to-surface tests.

The pull-out force is opposed by ordinary burdens and shear stresses following up on the addition surface. The non-uniform three-dimensional condition of pressure starts a concrete disappointment instrument, which does not have an accord in its comprehension. Expository and trial examines have endeavored to increase a comprehension of the principal disappointment system and have been effective in introducing considerable relationships between draw out power and compressive quality [2]. The normal incentive for the coefficient of variety for the draw out test has been seen as around 8% [2]. The elements that influence result variability are most extreme total size, concrete mortar rate, kind of addition, and profundity of implant [17]. These variables can be interceded by directing test-explicit connection diagrams that coordinate in qualities with the normal concrete examples of intrigue.

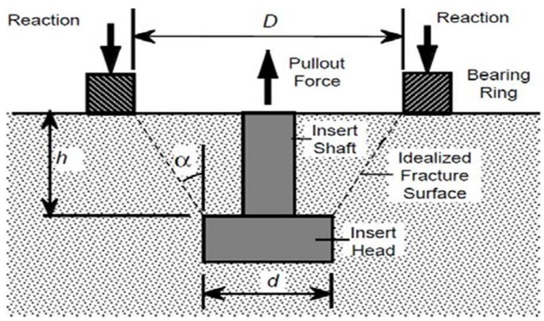

Fig. 3. Schematic diagram of typical pull-our resistance methods [2]

D. Pull-off resistance methods

The pull-off test is an in-situ quality appraisal of concrete which quantifies the malleable power required to pull a circle bonded to the concrete surface with an epoxy or polyester resin. The pull-off power gives an indication of the pliable and compressive quality of concrete by methods for built up observational connection graphs. The most ordinarily utilized pull-off test is the 007 Bond Test. The test comprises of a hand-worked switch, bond circles, a flexible arrangement plate, and power measures (Fig. 4a). The circle is bonded to the concrete surface by high quality cement and is joined to the hand-worked switch by a screw. After leveling the flexible arrangement plate, the pressure power is applied by the switch and estimated by the power check (Fig. 4b). The pull-off elasticity is determined by dividing the malleable power at the disappointment by the circle territory and is utilized to determine the compressive quality of concrete by using recently settled experimental connections. The following distributions present standard guidelines for pull-off opposition 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 evaluations of concrete quality by close to-surface tests.

The main bit of leeway of pull-off test strategies is that they are simples, fast, and could be utilized to test a wide scope of construction settings. A critical confinement is a curing time required for the cement, which is for the most part around 24 hours. Another impediment identifies with the human blunder in surface arrangement which may make the glue come up short. The outcomes for elasticity are frequently within 20% of the genuine rigidity [17]. The variables that most add to the variability of results are the size and sort of coarse totals [10, 11]. It is prescribed to create connection outlines using tests that match testing conditions and to direct the test a few times using diverse estimated circles in request to increase certainty by repeatability.

E. Resonant frequency test method

Resonant frequency strategies are non-invasive non-destructive tests that are directed to determine material properties by measuring their regular frequency of vibration. The two classes of resonant frequency techniques are resonant frequency by vibration and resonant frequency by the effect. The normal frequency of a vibrating auxiliary part is a component of its measurements, dynamic modulus of elasticity and thickness. Thusly, measuring either the transverse or longitudinal characteristic frequency of vibrations of a basic individual from known measurements and material permits the determination of its modulus of elasticity [15, 16]. It ought to be noticed that the following conditions were determined according to homogenous, isotropic, and completely versatile systems. The conditions are not met in the testing of in-situ concrete; nonetheless, the conditions despite everything give a precise gauge of material properties. The system involves an oscillator that produces

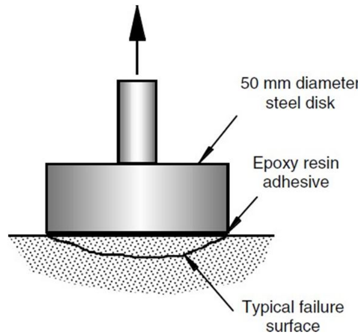

Fig. 4. (a)Typical setup of pull-out resistance NDT methods; (b) Schematic diagram of pull-out resistance NDT methods [10, 11]

mechanical vibrations and sensors that recognize the vibrations. The three most normally utilized sensors are removal sensors, speed sensors, and accelerometers. The standard guideline on testing and interpreting resonant frequency techniques in ASTM Standard C 215-85: Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens. The dynamic modulus of elasticity gives an indication of the mechanical integrity of auxiliary parts. The dynamic modulus of elasticity is commonly higher than the static modulus of elasticity, which is the suggested boundary in plan figuring. The variables affecting the resonant frequency and dynamic modulus of elasticity are the concrete blend extents, aggregate properties, basic example size, and curing conditions. These components ought to be considered when testing basic components that are not at all like the conditions outlined in ASTM C215-85. By the by, resonant frequency strategies give a brilliant way to studying the impacts of outrageous temperature changes and loading.

F. Maturity test method

The maturity strategy is an NDT method for deciding the quality addition of cement dependent on the deliberate temperature history during restoring. The maturity function is introduced to measure the impacts of time and temperature. The subsequent maturity factor is then used to decide the quality of cement dependent on built up relationships. The maturity technique has different applications in solid development, for example, formwork evacuation and post-tensioning. The factors that lead to inconstancy in testing are total properties, cement properties, water-cement ratio, and relieving temperature [17]. Temperature versus time is recorded by methods for thermocouples embedded into new solid (Fig. 5). The deliberate time history could be utilized to register a maturity file which gives a solid gauge of early age solid quality as a function of time [11, 18]. The standard rule on the testing and translation of the maturity technique is ASTM C 1074-11: Standard Practice for Estimating Concrete Strength by Maturity Method. Before endeavouring to assess the in-situ quality of solid, lab testing on solid examples of comparable attributes must be acted so as to build up the right maturity function while limiting the impact of the previously mentioned factors. Temperature test areas must be painstakingly chosen to quantify a delegate temperature of the whole solid segment.

Fig.5. Maturity test apparatus with thermocouple [11]

G. Permeation test method

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

- Pressure driven permeability which is the development of water through concrete.

- Gas permeability which is the development of air through concrete.
- Chloride-ion permeability which involves the development of electric charge.

The measuring of chloride penetrability is the most ordinarily used non-destructive strategy that provides an indication of concrete permeability through established correlations. The standard rule 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 cut, sealed with an epoxy covering from different sides, saturated in water and afterward positioned in a split-testing gadget loaded up with a sodium chloride solution with an applied voltage potential [17]. The charge passing through the concrete is then measured where:

- an estimation of somewhere in the range of 100 and 1000 Coulomb's represents low permeability
- a worth more noteworthy than 4000 Coulombs represents high permeability

H. Ultrasonic pulse-velocity test

Ultrasonic pulse speed methods include engendering ultrasonic waves in solids while measuring the time taken for the waves to proliferate between a sending and getting point. The features of ultrasonic wave propagation can be used to portray a material's composition, structure, elastic properties, density and geometry using previously established correlations, known patterns and numerical relationships. This non-invasive strategy is also used to recognize and describe flaws in material as well as their severity of harm by observing the scattering of ultrasonic waves. The basic procedure of ultrasonic pulse speed methods involves the transformation of a voltage pulse to a ultrasonic pulse and back by transmitting and accepting transducer respectively. The transmitting transducer is set onto the concrete surface and is permitted to transmit a ultrasonic pulse through the specimen medium. The ultrasonic pulse travels through the concrete specimen and is identified by an accepting transducer at the opposite end which transforms the ultrasonic pulse to a voltage pulse (Fig. 6). Knowing the distance between the two points, the speed of the wave pulse can be resolved. The speed of the ultrasonic pulse provides a point by point record of the specimen under scrutiny. The accompanying publications present standard guidelines for ultrasonic pulse speed testing:

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

Fig. 6. Ultrasonic pulse velocity test apparatus [13]

The factors adding to the variability of ultrasonic pulse speed methods as applied to the concrete are total properties, concrete sort, water-concrete proportion, admixtures, and period of concrete [13]. Additionally, inserted support in the pulse way may significantly affect the measurements of pulse speed [17]. By considering these factors during the analysis, ultrasonic pulse speed methods are astounding means for investigating the consistency and durability of concrete in a simple and inexpensive way.

I. Corrosin of resistance method

Corrosion of steel is an inescapable electrochemical and thermodynamically response that happens immediately because of the metallurgical trait of iron. Corrosion of steel support in concrete requires the loss of passivation, nearness of dampness, or potentially the nearness of oxygen. These conditions are frequently fulfilled in solid structures where corrosion must be postponed or eased back somewhere around protection measures and procedures. The subsequent iron oxides have one of kind synthetic, electrical, attractive, and electrical properties that could be abused so as to decide the degree of fortification corrosion by methods for NDT. Non-destructive techniques for testing support corrosion require the utilization of a half-cell framework and high-impedance voltmeters (Fig. 11). This framework is equipped for recognizing the current progression of particle relocation through the solid among anodic and cathodic locales by estimating the resultant equipotential lines [24]. The solid capacities as an electrolyte and the danger of corrosion might be connected observationally to the deliberate potential distinction that prompts corrosion. The standard rule on the application and understanding of fortification corrosion testing is ASTM C 876 - 91: Standard Test Method for Half-Cell Potentials of Uncoated

Reinforcing Steel in Concrete. The conditions for the fruitful testing are presentation and electrical coherence of fortification in the test zone. As indicated by ASTM 876, there is a:

- 90% likelihood of dynamic corrosion if the negative potential is more than - 350mV.
- 90% likelihood of no corrosion if the negative potential is not exactly - 200mV.
- Vulnerability in corrosion if the negative potential is between - 350mV and - 200mV.

The half-cell potential test is a valuable method to find likely dynamic territories of corrosion. It is suggested that potential overviews be enhanced with tests for carbonation and solvent chloride particle content for increasingly precise outcomes.

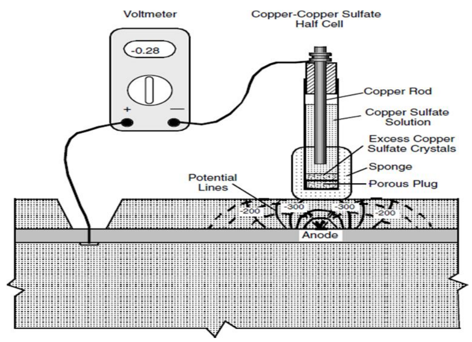

Fig. 7. Schematic drawing of half-cell apparatus [24]

III. Conclusions

A wide scope of non-destructive testing strategies has been investigated regarding their latent capacity, confinements, examination procedures, and understandings. The components that impact the achievement of NDT techniques were investigated and an approach to intercede their impact was suggested. It was discovered that most of NDT strategies depend on contrasting tried boundaries and built up relationships. Observational connections gave by producers were found to regularly give inadmissible outcomes. Where appropriate, it is prescribed to lead test-explicit relationship methodology for the NDT of cement. Advances in sensors, improvement of new materials, and scaling down of gadgets are generally preparing for new NDT techniques. Table 2 summarizes the merits and demerits of various NDT techniques which are commonly utilized for testing concrete materials and other RCC structures.

TABLE II. Merits and Demerits of Different NDT Techniques Utilized for Concrete Materials Testing [18-27]

NDT Techniques	**Concrete materials and reinforced concrete structures**	
	Merits	Demerits
Sound Ranging Based Techniques (Acoustic Based)	Higher levels of penetration power with high sensitivity Better level of Accuracy Cost-efficient Easy detection of sub-surface defects	Experienced and guided personnel are required to gain manual operational efficiency Non-homogeneous, rough and thin parts of materials cannot be evaluated Moisture affects the material detection process
RADAR Techniques	Structural inconsistencies can be easily found out even in layered structures Independent of Environmental conditions and quite fast The weaker diminution of Radar waves enhances its power to investigate concrete structures	Too much expensive Consistent and sound concrete may show delamination Minor defects cannot be detected Dielectric constant becomes a major explanatory factor during result assays Operator experience inclusive Metals and rebar cannot be penetrated by waves
Physical Techniques	Least expensive Easy elucidation	The results are easily modifiable based on characteristics like shape, size, age and rigidity of the concrete materials
Thermal Techniques	Contactless surface detection Safe and Cheap for Labour extensive tests Time and Equipment saving	The equipment utilized are quite expensive It is not a standalone technique for identification of source and cause of defects The data points after analysis are not sufficient
Penetration based Radiation Techniques	Thick layers or dense materials are generally investigated Shapes and forms cannot be calibrated	Too much expensive Radiation hazards are a limitation

Information combination strategies are being created to incorporate a few NDT techniques with the point of empowering viable information securing, preparing, and understanding of test boundaries according to material honesty. Much examination intrigue and industry consideration have been committed to the acoustic strategies of NDT. This is a consequence of a reasonable pattern in testing solid structures utilizing acoustic signs handled by programming utilizing propelled information investigation calculations. NDT of cement is progressively picking up acknowledgment as a method for assessing material honesty. Low mindfulness with respect to NDT techniques is blocking its take-up and is owing to an absence of comprehending development materials and NDT strategies themselves.

REFERENCES

[1] Bickley, J. (1982). The Variability of Pullout Tests and In-Place Concrete Strength. *Concrete International, ACI, Vol.4, No. 4* , 44-51.

[2] Carino, N. (2004). Pullout Test. In V. Malhotra, & N. Carino, *Handbook on Nondestructive Testing of Concrete* (pp. 24-56). New York: CRC Press.

[3] Dinh, K. & Zayed, T. (2013). Correlation based Model for Evaluating Ground Penetration Radar (GPR) Data of Concrete Bridge Decks. *In: Proceedings of 30th IAARC,* Montreal, Canada.

[4] Hussain, A. & Akhtar, S. (2017). Review of Non-destructive Tests for Evaluation of Historic Masonry and Concrete Structures. *Arabian Journal for Science and Engineering, Vol. 12, No. 2*, 20- 34.

[5] Helal, J., Sofi, M. & Mendis, P. (2015). Non-destructive Testing of Concrete: A Review of Methods. *Electronic Journal of Structural Engineering, Vol. 14, No. 1,* 97-105.

[6] Balayssac, J.P., Andrade, C., Monterio, J.S. & Scheel, H. (2012). Ruptures of Prestressing Cables. In D. Breysse (ed.) *Non-destructive Testing of Concrete Structures: Reliability and Limits of Single and Advanced Techniques*. Springer, Talence.

[7] Lombillo, I., Thomas, C. & Villegas, L., Fernandez-Alvarez, J.P. & Norambuena-Contreras, J. (2013). Mechanical Characterization of Rubble Stone Masonry Walls using Non and Minor Destructive Tests. *Construction and Building Materials, Vol. 43, No.4,* 266-277.

[8] De-Clereq, H., Hayen, R., Cnuddle, V., Boone, M. & Dusar, M. (2012). Damage Assessment of Ferruginous Sandstone by X-ray Tomography- The Virgin Tower of Zichem (Belgium). *In: Proceedings of the 12th International Conference on the Deterioration and Conservation of Stone, Columbia University, New York, USA*.

[9] Brozovsky, J. (2014). Calcium Silicate Bricks- Ultrasonic Pulse Method: Effects of Natural Frequency of Transducers on Measurement Results. *International Journal of Civil, Environmental, Structural, Construction, Architecture and Engineering, Vol. 8, No.9,* 971-974.

[10] Do, C.T., Bentz, D.P., Stutzman, P.E. (2007). Microstructure and Thermal Conductivity of Hydrated Calcium Silicate Board Materials. *Journal of Building Physics, Vol. 31, No. 1,* 55-67.

[11] Breyse, D. (2014). Non Destructive Assessment of Concrete Structure: Reliability and Limits of Single and Combined Techniques. Springer, Berlin.

[12] Brencinch, A., Cassini, G., Pera, D. & Riotto, G. (2013). Calibration and Reliability of the Rebound (Schmidt) Hammer Test. *Civil Engineering Architecture, Vol. 1, No. 3,* 66-78.

[13] Bagavathiappan, S., Lahiri, B.B., Saravanan, T., Philip, J. & Jayakumar, T. (2013). Infrared Thermography for Condition Monitoring – A Review. *Infrared Physical Technologies, Vol. 60, No.2,* 35-55.

[14] Matsumoto, M., Mitani, K. & Catbas, F.N. (2013). Bridge Assessment Methods using Image Processing and Infrared Thermography Technology: On-site Pilot Application in Florida. *In: Transportation Research Board 92nd Annual Meeting, Washington D.C., USA.*

[15] Hamidian, M., Sharati, A., Khanouki, M.A., Sinaei, H., Toghroli, A. & Nouri, K. (2012). Application of Schmidt Hammer and Ultra-sound Pulse Velocity Techniques for Structural Health Monitoring. *Science Research Essays, Vol. 7, No. 21,* 1997-2001.

[16] Hannachi, S. & Mohamed, N.G. (2012). Application of the Combined Method for Evaluating the Compressive Strength of Concrete on Site. *Open Journal of Civil Engineering, Vol. 2, No. 1,* 1-6.

[17] Concrete Institute of Australia. (2008). *Non- destructive Testing of Concrete.* Sydney: Concrete Institute of Australia.

[18] Bamforth, P. (2015). *Corrosion of Reinforcement in Concrete Construction* (pp. 348-350). New Yotk: Elsevier Applied Science.

[19] Henderson, G., Basheer, P., & Long, A. (2004). Pull-Off Test and Permeation Tests. In V. Malhotra, & N. Carino, *Handbook on Nondestructive Testing of Concrete* (pp. 64-83). New York: CRC Press.

[20] Kolek, J. (1969). *Non-destructive testing of concrete by hardness methods.* London: Institute of Civil Engineers.

[21] Malhotra, V. (2004). Surface Hardness Methods. In V. Malhotra, & N. Carino, *Handbook on Nondestructive Testing of Concrete* (pp. 1-9). New York: CRC Press.

[22] Malhotra, V., & Carette, G. (2004). Penetration Resistance Methods. In V. Maholtra, & N. Carino, *Handbook on Nondestructive Testing of Concrete* (pp. 10-23). New York: CRC Press.

[23] McCann, D., & Forde, M. (2001). Review of NDT methods in the assessment of concrete and masonry structures. *NDT&E International* , 71- 84.

[24] Naik, T., Malhotra, V., & Popovics, J. (2004). The Ultrasonic Pulse Velocity Method. In V. Malhotra, & N. Carino, *Handbook on Nondestructive Testing of Concrete* (pp. 84-97). New York: CRC Press.
[25] Shull, P. (2002). *Nondestructive Evaluation: Theory, Techniques and Applications.* New York: Marcel Dekker, Inc.
[26] Sohn, H., Farrar, C., & Hemez, F. (2004). *A Review of Structural Health Monitoring Literature from 1996-2001*. Los Alamos: Los Alamos National Laboratory.
[27] Workman, G., & O. Moore, P. (2012). *Nondestructive Testing Handbook 10: Overview.* Columbus: American Society of Nondestructive Testing.