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Non-destructive Testing Methods of Reinforced Concrete Structures- A Critical Review

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Abstract

The investigation of microstructural characteristics and health monitoring of concrete structures are of great importance for the prevention of concrete failure and rehabilitation of concrete. Existing structures require testing for their structural characteristics. These properties are to be obtained without alterations in the structural orientation of the concretes. To achieve this, non-destructive testing techniques become preferable as the testing of the properties are obtained without deformation of concrete structure. In this study, a comprehensive review of the concrete structures is presented. The application of varying non-destructive testing techniques for the determination of physical, chemical, mechanical and durability properties of concrete structures are reviewed. Also, various non-destructive testing methodologies are examined; the application areas and limitations are presented. It was also verified that the microstructural properties of concrete could be determined through non-destructive testing method.

Keywords: concrete, Non-destructive, testing, deterioration, durability

1.0 Introduction

Based on durability challenges, researchers and Engineers frequently carry out assessment of existing buildings across the world. The assessment of in situ compressive strength of a reinforced concrete structure plays a vital role in the estimation of its safety. The determination of concrete strength in existing structures becomes crucial for assessing their seismic capacity. Prior to construction, concrete strength is measured using control specimens. Traditionally, the compressive failure load on concrete cube or cylinder is measured and divided by the cross-sectional area. However, destructive tests with the objective of gathering sufficient data on the residual strength of reinforce concrete at an affordable cost.

Non-destructive testing plays an important role in the identification and detection of internal defects and cracks in many industrial applications such as concrete structures, pavements and metal testing. Non-destructive testing of reinforced concrete structures allows the inspection of larger areas of concrete members at lesser cost than curing and provides more detail information than visual inspection (Wankhade and Landage, 2013).

The process of evaluating and tracking structural integrity and assessing the nature of damage in a structure is referred to as health monitoring (Chang et al, 2003). According to available data, plethora of works have been carried out on infrastructure monitoring, inspection, repair and design code specifications. For instance, in the

United States of America (USA), in every two years, about 600,000 bridges are inpected and depending upon their condition, they are scaled (Pines and Aktan, 2002).

Federal Highway Administration (FHA) has provided a scaling system (0 – 9) for a thorough rating of all structures. Rating done so far revealed that more than 40% of the national bridges are structurally deficient (Pines and Aktan, 2002). Furthermore, these fall short of the expected average life of bridges in the USA. The average life was found within 42 years whereas, bridges are designed and constructed for at least 50 years (Herrmann, 2013).

Therefore, it becomes crucial to carry out thorough health monitoring and maintenance of concrete structures. Two categories of structural health monitoring has been identified i.e. global health monitoring which is the technique that involve only the occurrence of damage is detected whereas, local health monitoring, the extending location and severity of damage is identified (Chang et al, 2003). It is imperative to carryout both global and local health monitoring.

Non-destructive test (NDT) and non-destructive evaluation (NDE) enable engineers and researchers to effectively assess and monitor existing structures. These methods are used to evaluate the extent of damage in a structure. It is essential to carryout NDT to avoid unexpected and sudden collapse of structures. Various methods and guidelines have been provided to be comprehensive for the assessment of structures (Mccann and Forde, 2001; Scott et al, 2003; Mori et al, 2002).

Concrete structures over time, deteriorate and develop defects. These defects reduce the structural capabilities of the concrete. In order to prevent or remedy these problems, the materials are tested or monitored to detect these defects. Destructive testing techniques are not recommendable for existing structures. Therefore, non-destructive testing methods become imperative for testing and monitoring of concrete structures.

Therefore, this study aims to carry out a critical review on the non-destructive testing of concrete material. The aim would be achieved through the following objectives;

i. Comprehensive review of studies carried out by researchers on the determination of the physical, chemical, mechanical and durability properties of concretes using non-destructive testing methodologies.
ii. The evaluation of different non-destructive testing techniques.

2.0 LITERATURE REVIEW

This section presents detailed review of studies carried out using non-destructive testing of concrete materials and structures. The review captures the use of non-destructive testing techniques on the physical, chemical, mechanical and durability properties of concretes. The chapter also captures the different techniques of non-destructive testing of concretes; their methodologies, advantages and limitations.

2.1 Non-destructive Testing of Physical Properties of Concretes

Joshaghani and Zollinger (2017) implemented Groung-Penetrating Radar (GPR) and percometer for newly constructed highways. The GPR, a non-destructive testing technique, identified the subsurface condition which permits the determination of moisture availability for potential concrete curing. To calculate the Effectiveness Index (EI), Dielectric Constant (DC) measurements were carried out on concrete specimens to indicate relative humidity and temperature. The effectiveness of the applied curing compounds in terms of moisture retention capability was diagnosed through a combined GPR information evaluation and curing quality evaluation. Also, the relationship between non-destructive testing data and actual concrete properties to develop acceptability of quality limits based upon the NDT data.

The researchers observed that during replacement by ground penetrating radar (GPR) and percometer, the dielectric constant (DC) measurement could be conducted. Data collection of GPR was observed to be relatively straightforward and might cause problems in rainy days due to conversion of required GPR signals from wet surfaces.

Ozturk et al (2019) investigated the dispersion and orientation of fiber reinforced concretes through non-destructive testing technique. The dispersion and orientation of fibers were determined through extraction of electromagnetic properties of the structures in microwave regime. The measurement employed sample under test (SUT) and two wideband linearly polarized antennas placed in front and backside of material under free space condition.

From the study, the correlation between electromagnetic properties and fiber orientation in microwave frequency region. The determination fibers orientation and dispersion was made possible by measuring electrical parameters of the medium. The method proposed by the study made the determination of dispersion and orientation of fibers in concrete easy, cheap and non-destructive to conduct on construction site. With this method, the intensity of fibers in concrete could be easily detected and also casted concrete thereby, saving costs and better qualified fiber reinforced concretes.

Polimeno et al (2018) investigated the modifications caused by seismic loads on reinforced concrete buildings through the application of two non-destructive test methods; ultrasonic and wave propagation. The research aimed at delineating a quick and easy method to be applied on-the-field to provide stat of the health information of the reinforced concrete structure. Shaking table tests reproducing several earthquakes were applied in the experiment using the Italian code NTC 2008. The direct and indirect sonic methods and partial and complete approaches for ultrasonic tomography were employed.

The experimental results showed the capability of the employed techniques in the detection of structural damage to reinforced concrete and provided an estimation of the health of the building. Information obtained from the sonic test could be applied to the assessment of global state of health of reinforced concrete structures in accordance with global damage indicators like the ones obtained from modal frequency evolution and inter-storey drift ratios.

It was noted however, that the applied method was not suitable for application in places where walls impede access to columns. This is due to the discovery that ultrasonic measurement, as well as tomographic reconstructions require access to all faces of columns of reinforced concrete buildings.

Saenger et al (2011) applied time reverse modelling (TRM) to localization and characterization of acoustic emission using a numerical concrete model. Rotated staggered finite difference grid was used to calculate effective elastic properties of concrete. The numerical modelling, an efficient and well-controlled computer experiment showed that source areas and characteristics of acoustic emissions can be located using time reverse modelling.

Rifai et al (2018) using non-destructive testing techniques, investigated the in-situ pore size of loaded porous concrete under increasing pressure with two different non-destructive analytical methods; Nuclear Magnetic Resonance (NMR) and X-ray

Computed Tomography (CT). The results obtained were comparable and complementary. The NMR could detect the behavior of small pores. CT revealed that some pores collapse and the increase of the small pore sizes is not mainly caused by additional cracks but by pores crashing and debris material.

2.2 Non-destructive Testing of Chemical Properties of Concretes

Abbas et al (2018) carried out a comparative analysis of the limitations and prospects of the various techniques employed in the non-destructive in situ measurement of chloride ions concentration in concrete. The study focused on application of electrochemical and electromagnetic techniques. The various advantages and disadvantages of the techniques examined were highlighted.

Electrochemical and electrical techniques examined include potentiometric measurement, chronopotentiometric measurement and electrical resistivity and impedance analysis. A Ag/AgCl chloride ion selective electrode was used. In the potentiometric measurement, a zero-current technique, the circuit potential of an embedded Ag/AgCl electrode is measured against a reference electrode.

The electromagnetic techniques assessed include fiber optic sensor, Laser breakdown spectroscopy, Nuclear Magnetic Resonance (NMR) and X-ray diffraction analysis. The electromagnetic techniques were characterized into embedded and non-embedded techniques. A fiber optical sensor with optical transducer, sensitive to chloride is embedded in concrete in the embedded technique. These sensors are relatively inert to environmental factors, geometric factors and ion interference. The researchers noted that the technique used was restricted to long-term in situ measurement due to lifetime of optical transducers, bulky measurement set up and extra protection of fibers. However, the non-embedded technique with external excitation, such as laser breakdown and near field spectroscopy, seem ideal due to the complete non-invasiveness and contactless nature. But this technique was noted to lack selectivity, portability and local chloride ion measurement.

Torres-Luque et al (2014) investigated the chloride ingress into chloride and developed state of the art of non-destructive and in suit techniques for measuring chloride content into concrete structures. The methods are based on electrical resistivity (ER), ion selective electrode (ISE) and optical fiber-sensors (OFS).

The ion electrode selective method was noted to be capable of distinguishing chloride ion ingress though affected by alkanility, temperature and geometrical position. Electrical resistivity technique was also noted to be a non-embedded and non-invasive technique. However, it is affected by degree of humidity of the concrete surface, distance of the rebar, carbonation presence and electrical fields. The optical fiber sensors were noted to be the most promissory technique. They were observed not to be affected by geometrical distribution, ions presence, environmental factor or electromagnetic fields. However, the fiber needs an extra protection to isolate it from corrosive environment.

The researchers recommended that research efforts should focus on the improvement of the accuracy of the non-destructive tests under in-field exposure conditions.

Derobert et al (2017) carried out an evaluation of chloride contamination in concrete using electromagnetic non-destructive testing methods. Methods employed include resistivity quadripole probe, capacitive technique with few set of electrodes, radar technique using different bistatic configurations. Three different concretes with varying water to cement ratios were examined in the laboratory. The three groups contained 0 g/L, 30 g/L and 120 g/L of NaCl saturation. Three indicators investigated are chloride content, saturation rate and porosity.

From the result, all techniques were sensitive to presence of chlorides. The techniques were though not very sensitive to porosity and saturation rate. Experiments on a real site in a marine environment have shown that the porosity and saturation rate important for a proper estimation of chloride content through a multi-linear regression approach.

Xu and Jin (2018) in their study, measured concrete corrosion through ultrasonic-based non-destructive test and artificial neural network by applying ultrasonic to reinforced concrete members, ultrasonic velocities were tested before and after the rebar corrosion. Also, the predictive models for the prediction of corrosion level with concrete strength, ultrasonic velocity and specimen dimension-related variable as input variables using artificial neural network.

The corrosion depth of the reinforced concrete was found to be between 80 μm and 200 μm. The rebar corrosion in the concrete was observed to have caused significant reductions in ultrasonic velocity.

Arterrieu et al (2019) in their study, presented a numerical tool allowing effective prediction of corrosion rate (Vcor) data from non-destructive test measurements. The numerical tool presented allowed application of different assimilation techniques. Four data assimilation techniques were employed; NDT fusion, Cokriging, Bayesian sequential simulation (BSS) and decision tree (supervised learning). The four integration methods are included in an operating system that is being finalized, allowing only for integration of multi-scale and multivariate data.

Watanabe et al (2019) carried out a non-destructive chemical analysis of water and chlorine content in cement paste using near-infrared spectroscopy. Cement paste samples with varying chloride-ion concentrations and humidity were prepared for different types and reflectance spectra obtained, then moisture content and chloride ion concentrations were measured using destructive testing as reference.

From the result obtained, correlations between water and chloride concentrations and their respective near-infrared absorption values were observed to be higher than those of High early-strength Portland Cement (HPC) and blast furnace slag cement type B (BBFS).

The applied method was also noted to have a promising advantage aside its non-destructive nature; simultaneous analyses of multiple components in concrete within an approximate time of one minute. It is highly sensitive and can easily sense the chloride induced deterioration of concrete member well before damage can be worsened.

Sadowski (2015) carried out a study employing three non-destructive testing techniques and artificial neural networks for the identification of values of pull-off adhesion between concrete layers in floors. Three stages were used in the methodology; determination of parameters of concrete by the non-destructive testing scanning, training and testing of artificial neural networks and numerical analyses of the results obtained to obtain the values of pull-off adhesion. This methodology proved to be practicable.

Sadowski et al (2016) applied two non-destructive test techniques and artificial neural networks (ANNs) for the identification of the value of value of pull-off adhesion between a concrete added layer with a constant thickness and a substrate concrete layer in existing elements. The non-destructive methods employed are impact-echo and impulse response on the surface of the added layer.

The methodology employed proved to be applicable in the identification of pull-off adhesion between concrete added layer with constant thickness and a substrate existing in the element.

2.3 Non-destructive Testing of Mechanical Properties of Concretes

Tsioulou et al (2017) investigated the reliability of non-destructive test (NDT) methods for the evaluations of compressive strength and the modulus of elasticity of ultra-high performance concrete (UHPC) and ultra-high performance fiber-reinforced concrete (UHPFRC). The actual mechanical characteristics obtained from mechanical tests, Ultrasonic Pulse Velocity (UPV), Rebound Hammer (RH) and combined SonReb techniques were examined.

The reliability of theoretical models for the estimation of modulus of elasticity of homogenous elastic medium for UHPC and UHPFRC using the UPV measurements were evaluated and the following observations were made.

The compressive strength of UHPFRC with 3% steel fiber was slightly higher than the value for UHPC (without steel fiber). The modulus of elasticity was not considerably affected through the post-cracking response of the material but is significantly enhanced by the increment in the percentage of steel fiber.

The combined SonReb method showed the lowest error in the estimation of strength and modulus of elasticity. Therefore, the SonReb method was recommended for the reliable prediction of compressive strength and modulus of elasticity of UHPC and UHPFRC.

Velay-Lizancos et al (2018) studied the influence of fine and coarse recycled aggregate of concrete (jointly) with emphasis on the evolution of elastic modulus and its relationship with compressive strength and non-destructive testing. The evolution of elastic modulus was monitored using E-Modulus Measurement through Ambient Response Method (EMM-ARM). Two non-destructive test methods were examined; ultrasonic pulse velocity and electrical conductivity.

The replacement of natural aggregates with recycles aggregates was observed to have a clear influence on the relationship between Elastic Modulus and the Non-Destructive Test method used; ultrasonic pulse velocity and electrical conductivity. In both methods, it was observed that for same value of NDT, the higher the amount of recycled aggregate, the lower the corresponding Elastic modulus.

Also, at early ages, the correlation relationship between Elastic modulus and compressive strength was affected by the amount of recycled aggregate.

Singh and Singh (2018) in their work, investigated into the performance of self-compacting concrete (SCC) made with different replacement levels of Recycled Concrete Aggregate (RCA) via the use of Non-Destructive Testing (NDT) techniques. Different mixes of SCC were made with varying coarse recycled concrete aggregate and fine recycled concrete aggregate. The non-destructive testing techniques used include Electrical Resistivity, Ultrasonic Pulse Velocity and Rebound Hammer. The recycled aggregates were used as replacement of natural aggregate in the mix design. The compressive strengths of the concrete mixes were tested at various curing ages.

The compressive strength of the self-compacting concrete mixes were observed to decrease on increasing amount of addition of recycled concrete aggregate at all curing ages. The electrical resistivity was observed to reduce on increase in percentage replacement of natural aggregate with recycled concrete aggregate.

Also, linear relationship between compressive strength, electrical resistivity, ultrasonic pulse velocity and rebound number through linear regression analysis showed excellent correlation coefficient. Excellent correlation coefficients were obtained for concrete mixes with low and intermediate replacement levels of recycled concrete aggregate.

Al-Mufti and Fried (2012) investigated the early age behavior and properties of recycled concrete aggregate concrete in relation to normal concrete via non-destructive testing. Ultrasonic Pulse Velocity (UPV) and surface hardness test were carried out on the concrete mixes in both fresh and hardened stages.

From the tests carried out, the compressive strength and UPV of concrete mixes of normal concretes were higher than concretes with recycled concrete aggregate. However, the surface hardness of concretes mixes with recycled concrete aggregate were higher than those of normal concrete mixtures.

Also, it was noted that Ultrasonic Pulse Velocity is reliable method determining setting time concrete. This was established to be 2 hours after the point of maximum increase in UPV measurement.

Tan et al (2018) evaluated the compressive strength of coral aggregate seawater concrete (CAC) by non-destructive test technique. The CACs were cast at varying compressive strength (30 – 75 MPa). Ultrasonic Pulse Velocity, Rebound Hammer and compressive strength tests were carried out on specimens after 28 days and 90 days. The study also discussed the influence of sisal and age on the relationship between compressive strength and ultrasonic pulse velocity and compressive strength and rebound hammer. Also, mathematical model of strength prediction by ultrasonic pulse velocity, rebound hammer and combined method were established (testing strength curve, TSC).

The result showed that sisal content effect on compressive strength – UPV was less affected but curing age had more effect on the relationship between compressive strength and rebound hammer.

Juimo Tchamdjou et al (2018) evaluated the mechanical properties of lightweight aggregates concrete made with Cameroonian volcanic scoria using non-destructive characterization. Schmidt Rebound Hammer (SRH) and Ultrasonic Pulse Velocity (UPV) were performed on the concrete specimens to determine the concrete rebound number and dynamic modulus of elasticity at 28, 56 and 90 days. Two groups of concrete with volcanic scoria were prepared; first group produced with natural sand from Covilha – Portugal was cast in a cubic mould (150×150×150 mm) and the second group with natural sand from Rabat – Morocco was cast in cylindrical moulds (160×320 mm). Destructive test method was employed for the determination of compressive strength of cylindrical specimens.

From the study, the ultrasonic pulse velocity of concrete with small volcanic scoria and concrete with large crushed volcanic scoria was found to be around 3.20 -3.73 km/s for all curing time. According to the UPV value obtained, the concrete can be qualified as poor or fair/medium concrete. At 28 to 90 days, the volcanic scoria concrete specimen's dynamic modulus increased by 5.2 – 22.3% with corresponding UPV increase by only 4.2 – 7.4%. Also, 15.0 – 22.3% and 5.2 – 15.2% increment of compressive strength were recorded for the small volcanic scoria concrete and large volcanic scoria concretes respectively.

Sykora et al (2018) carried out an assessment of compressive strength of historic masonry using non-destructive and destructive techniques. From the study, the researchers noted that crude estimates of masonry unit strength based on non-destructive tests can be significantly improved by structure-specific calibration based on a few destructive tests. It was noted that non-destructive tests without calibration were not recommended for reliability assessments of historic masonry structures.

Combined usage of non-destructive tests and destructive tests provide useful information for the assessment of reliability of historic masonry structures.

Xu and Li (2018) in their study implemented rebound hammer as a non-destructive test technique and compressive tests of the core sample drilled from the concrete as destructive test technique to determine the spatial viability of the mechanical properties of concrete respectively. The strength of the concrete beams at different locations were estimated by rebound hammer.

Four mechanical properties; elastic modulus, peak strength, peak strain and post-peak energy per unit volume were obtained from stress-strain curves obtained from the compression tests. Also, values of compressive strengths were obtained by rebound hammer tests at the different locations of the beam.

Pucinotti (2015) carried out a non-destructive in situ assessment on the mechanical strength of important historic building in Reggio Calabria. Both rebound hammer and ultrasonic pulse velocity methods of non-destructive testing were applied in the test of concrete strength. While the rebound hammer method showed poor correlation and low level of significance of the identified parameters, the ultrasonic pulse velocity method showed more satisfactory result with better correlation value. However, the use of combined method (SonReb) increase the accuracy of the estimation of the in situ strength.

Craeye et al (2017) implemented combined non-destructive techniques to on-site strength assessment of limestone based concrete slabs. The rebound hammer, ultrasonic pulse velocity, Wenner probe for concrete resistivity and Windsor probe (a semi-destructive test) were implemented in the tests to determine the concrete compressive strength. The different methods were compared and it was observed that combining the different non-destructive testing methods could increase the quality of fit of the obtained correlation curves. However, the researchers noted that combined non-destructive test methods (SonReb, SonPen, PenReb) are promising techniques for the determination of strength.

2.4 Non-destructive Testing of Durability Properties of Concretes

Nakarai et al (2019) investigated the effect of age on transport property measurement of concrete cover through non-destructive tests. Changes in air permeability, moisture contents and water sorptivity were monitored for three years through non-destructive test on site-cast concrete box culverts and mock-up specimens. In addition, carbonation rates of the specimen were measured.

From the study, the carbonation rates of the specimens were observed to have been affected by the type of cement and curing period. The air permeability and water sorptivity coefficients measured using non-destructive testing increased as the moisture content decreased over time. The long-term measurement showed that it took over two years to observe just after three years. Also, it was observed that high correlation existed between carbonation rates and air permeability and water sorptivity coefficients.

Castro et al (2015) applied a non-destructive technique in the determination of water penetration depth of concrete. The method of estimation employed microwave near-field measurement using an open-ended rectangular waveguide. The water penetration depths were determined from the differential measurement of reflection coefficient in the s-band, before and after injection of water under pressure.

The results obtained indicate that the method can be employed as an indirect method to estimate water penetration depth for the determination of permeability with good correlation with standard destructive test. The method was free from drilling out a sample from the structure, thereby reducing cost and duration of the analysis procedure.

Neves et al (2018) assessed the residual service life of carbonated structure reinforced concrete structures through the application of non-destructive test techniques. The test measured cover depth and carbonation of drilled cores. The methodology applied could measure the air-permeability from which the carbonation rate could be estimated.

The method could be used to determine on site, the air-permeability and cover depth in non-destructive manner, saving cost of drilling and cores.

Mizuta et al. (2024) developed a nondestructive test method to monitor the movement of water in concrete using neutron imaging. This technique could be very useful in the maintenance of concrete structure.

Bensaber et al. (2023) studied the effect of stress conditions on nondestructive testing methods. An experimental testing was conducted on the aged concrete using both destructive tests and nondestructive tests. Results showed that the stress conditions affect the NDT results.

2.5 Non-destructive Testing Methods

The classification of non-destructive testing are done on the basis of test sources, nature or methodology of test and purpose of test. In this study, the classification of non-destructive test on the basis of the test sources shall be adopted in accordance to the work of Rehman et al (2016).

2.5.1 Methods Based on Audio-Visual Techniques

2.5.1.1 Chain Drag

This method of non-destructive testing is carried out in accordance to ASTM D 4580-86. It is used to mark the delaminated areas on the surface of deck. The procedure of the test involve laying the grid system on bridge deck, then chains are dragged on the surface of the deck with the areas with dull and hollow sound is heard by the operator are marked. Finally, a map is prepared for locating these delaminated areas with the use of grid lines.

However, this method cannot be applied to the testing of vertical surfaces. It may not be able to detect initial delaminations in concretes and are ineffective on bridge decks with overlays.

2.5.1.2 Visual Inspection

This is a versatile non-destructive test method applied to visible surfaces. It is mostly used for monitoring of damages in concrete structures. It is usually implemented to determine cracks, seepage, spalling, exposed reinforcement, staining, moisture ingress, beam delamination, reinforcement corrosion and concrete deterioration.

The effectiveness of visual inspection is dependent on the experience and knowledge of the investigator. The major setback of this method is that cracks, damages and deterioration are only detected when the life of the structure begins to be affected.

2.5.2 Methods based on Stress-Wave

2.5.2.1 Acoustic Emission (AE) Test

This test method is applied mostly for damage detection in several fields especially transportation sector. It is based on transient elastic waves; the waves are produced from the structure under observation by rapid release of energy and the transducers are used to collect these waves.

This method is limited by the problem of background noise problem, difficulty in application of analysis to real structure and absence of standard for all types of bridges.

2.5.2.2 Impact Echo Testing

This method, a stress-wave method of non-destructive testing as used for the detection of flaw and determination of the thickness of structural member.

2.5.2.3 Sonics Method

This is a stress-wave non-destructive method used previously for the determination and assessment of civil structures and materials. In this method, stress waves are transmitted mechanically into the structures. These waves are reflected and collected by the receivers. The transmission modes are direct, semi-direct and indirect. Furthermore, sonics method can be employed in the evaluation of effectiveness and distribution of grout in structures.

2.5.2.4 Ultrasonic

This method is also known as ultrasonic pulse velocity and is employed in the determination of the relative condition of concrete by measurement of time of pulse of ultrasonic waves across a length. The setup consists of transmitting and receiving transducers. Stress pulse, propagated in the structural members are produced in the transmitting transducers whereas, the signals are then received by the receiving transducers.

Some of the limitations of this testing method include the following; requires very close grid spacing, time consuming, difficulty in coupling the sensors on rough surfaces, may not detect shallow defects and some defects may remain undetected due to use of low frequencies.

2.5.2.5 Impulse Response

This method is also known as sonic mobility. It is mainly applied to deep foundations. The method employs low-strain impact to produce the stress waves. Compressive stress waves are generated when hammer strikes the concrete. The frequency of the compressive stress wave from 0 to 3000 Hz depending on the material used in the hammer. The forces are measured by load cell while the velocity is measured by the receiver.

This method is limited by some challenges; reliable data are highly dependent on the selected point, smaller defects may remain undetected and scarcity of automated apparatus.

2.5.3 Methods Based on Electro-magnetics

2.5.3.1 Ground Penetrating Radar

This method is mostly used for the investigation of bridge decks and pavements. It produces electromagnetic wave-reflection survey used for monitoring of health of structural members. The method is a rapid and quick method for assessing in-depth characteristics of subsurface layers of concrete. Cracks, delaminations, cavities, damages, moisture content can be determined by this method.

However, it is cannot direct images. The method cannot detect delaminations on bridge decks except they are epoxy-impregnated or filled with water. Its data reading are not very reliable in extremely cold conditions. Also, it is a very expensive method when compared to other methods.

2.5.3.2 Electromagnetic Conductivity

The method provides geometrical and electrical information and degree of saturation about the materials. When conductivity characteristics of concrete indicates the damage in concrete. It employs the response of the ground against the propagation of electromagnetic fields. The electromagnetic fields generated through transmitting coils, passes through the object and their responses are monitored.

2.5.3.3 Half-cell Potential

This is an electrical testing method used for the evaluation of corrosion activity of steel reinforcement. It is a method that is not affected by time or climatic conditions hence, it can be employed at any time and under any climatic condition.

However, it cannot be used for moisture or salt content calculation. Readings cannot be obtained on the isolating surface and in most cases, the measurement are not very reliable due to wet nature of material.

2.5.3.4 Electrical Resistivity

This method is the direct opposite of the electromagnetic conductivity. The electrical resistivity of concrete is the ratio of applied voltage and resulting current in a unit cell. In the testing method, minimum of two electrodes are used out of which one is the reinforcing steel bar. Voltage/current is applied between the electrodes and resulting current/voltage is measured. The ratio of the voltage to the current gives the resistance of the material. The resistivity is calculated by multiplying resistance with a factor; cell constant.

The testing method is used in detecting cracks, moisture presence, susceptibility of concrete to corrosion and regions susceptible to chloride penetration. This method provides raw data which are sometimes difficult for interpretation. It depends on the material properties such as moisture content, porosity and salt content. The surface to be investigated has to be pre-wetted before testing is carried out.

2.5.4 Deterministic Methods

2.5.4.1 Proof Load Test

The actual load carrying capacity of structure are determined by this method. It also can be used as a diagnostic test method to verify analytical or predictive structural models. The methods becomes appropriate when unsatisfactory load rating is indicated by the analytical procedures or it is not possible to perform analytical test on structure due to lack of structural documentation or deterioration.

2.5.4.2 Coring

This method, though considered to be a semi-destructive method, is used to determine the internal defects in structures. Cores are extracted to measure the compressive, splitting tensile and flexural strengths of the concrete.

2.5.5 Dynamic/Vibration Testing

This method is mostly employed in the measuring of structural health of structures. Structures to be assessed are subjected to excitation forces and the responses are measured by means of transducers. This method can be applied to long span bridge during construction and rehabilitation stage.

2.5.6 Infrared Thermography

This method of non-destructive testing enables a large surface of concrete to be inspected in a short time/period. It is used to detect delaminations and anomalies in concrete surfaces. However, the method cannot detect deep flaws and cannot give information about the depth of cracks.

2.5.7 Radiography

This is a nuclear non-destructive testing technique in which high energy electromagnetic radiation passing through the test object is recorded on a photographic film placed on the other side of the member. The method is applied to detect reinforcement location, voids in concrete material, heterogeneity and layers of different materials.

3.0 CONCLUSION AND RECOMMENDATION

3.1 Conclusion

This study aimed at reviewing non-destructive testing of concrete materials. Critical review of non-destructive testing methodologies in the determination of the physical, chemical, mechanical and durability properties of concrete. The review has shown the reliability and applicability of some non-destructive testing methodologies in the investigation of structural characteristics of concretes. Non-destructive testing has been found to be effective in the investigation and determination of properties of existing concrete structures.

Microstructural properties of concrete could be determined through non-destructive testing of concrete. Also, through non-destructive testing of concrete, the health of concrete materials and structures could be monitored. The review revealed that plethora of works have been carried out on the monitoring, repair and design of methods for the testing of concrete in a non-destructive approach.

Furthermore, in this study various non-destructive testing techniques have been examined. The review revealed their various areas of applications and limitations. Non-destructive testing of concrete techniques has been observed to be very effective in the investigation of concrete properties.

3.2 Recommendations

Non-destructive testing of concrete has been revealed to be very effective in the determination of structural characteristics of concrete and the health monitoring of the concrete structure. There is no destruction of the structures to be examined. This therefore makes non-destructive testing a recommendable method for the determination of properties of concrete.

Furthermore, various non-destructive testing methods have been observed to have some limitations. Therefore, it is recommended that relevant techniques be employed in the investigation of concrete properties under certain conditions. Hence, it is imperative for investigators to have a good knowledge of the capabilities and limitations of the various non-destructive testing techniques.

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