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Review Article

Review of Nondestructive Testing Methods for Condition Monitoring of Concrete Structures

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The deterioration of concrete structures in the last few decades calls for effective methods for condition evaluation and maintenance. This resulted in development of several nondestructive testing (NDT) techniques for monitoring civil infrastructures. NDT methods have been used for more than three decades for monitoring concrete structures; now it has been recognized that NDT plays an important role in the condition monitoring of existing RC structures. NDT methods are known to be better to assess and evaluate the condition of RC structures practically. This paper reviewed several available NDT methods developed and used in the last few decades.

1. Introduction

Testing and quality checkup are important at different stages during the life of a structure. To properly maintain the civil infrastructures, engineers required new methods of inspection. Better inspection techniques are needed for deteriorating infrastructure (Rens et al., 1997) [1]. The traditional method of evaluating the quality of concrete in civil structures is to test specimens casted simultaneously for compressive, flexural, and tensile strengths; these methods have several disadvantages such as results are not predicted immediately, concrete in specimens may differ from actual structure, and strength properties of a concrete specimens depend on its size and shape; therefore to overcome above limitations several NDT methods have been developed. NDT methods depend on the fact that certain physical and chemical properties of concrete can be related to strength and durability of structures. These methods have been used for more than three decades for evaluating the condition of a structure; now in the present century NDT has become more sophisticated, as it has developed from a hammer to Impact Echo and Impulse response (Lim and Cao, 2013) [2].

NDT has been defined as comprising methods used to examine objects, materials, or systems without impairing their future usefulness, that is, inspect or measure without harm. NDT methods are now considered as powerful tools for evaluating existing concrete structures with regard to their strength and durability. NDT methods have been drawing more and more attention, in the sense of reliability and effectiveness. The importance of being able to test in situ has been recognized, and this trend is increasing as compared to traditional random sampling of concrete for material analysis (Shaw and Xu, 1998) [3]. NDT methods may be categorized as: penetration tests, rebound tests, pull out tests, dynamic tests, and radioactive methods. According to McCann and Forde (2001) [4]; five major factors that need to be considered in NDT survey are required depth of penetration, required vertical and lateral resolution, contrast in physical properties between target and its surrounding, signal to noise ratio for the physical properties between the target and its surroundings, and historical information concerning the methods used in the construction of the structure. Breysse et al. (2008) [5] described the various aims of NDT methods such as to detect the condition of RC structures, rank the structures according to present condition, and compare the different properties based on threshold values.

It is better practice that NDT engineers have the knowledge and training of various NDT methods available for testing a parameter, to select better technique form the available methods according to the condition of structures. Use of different methods for evaluating a single parameter increases the confidence and also validates the results. Combining the results of various NDT methods for assessing the quality of structures has been required for better results; this aspect has been discussed in the present paper.

This paper also presents brief literature review of the recent NDT tests performed on concrete structures, followed by a table describing advantages, limitations, and principle of several NDT methods, and also present status and future aspects of NDT methods have been discussed followed by a table presenting various codes describing these methods.

2. Brief Literature Review

Nondestructive techniques are useful for evaluating the condition of structure, by performing indirect assessment of concrete properties. These techniques have been improved in last few years and the best part is that NDT avoids concrete damage for evaluation. Several researchers perform NDT tests to evaluate the condition of concrete structures. Methods range from very simple to technical depending on the purpose.

Several mechanical and physical properties of concrete structures can be used to assess the condition and capacity of the structures. Sanayei et al. (2012) [6] performed static truck load test on a newly constructed bridge, to capture the response of bridge when a truck traveled across it. Amini and Tehrani (2011) [7] designed experimentally four sets of exposure conditions, weight and compressive strength of the samples had been measured before and after the freeze thaw cycles, and the results were analyzed. Loizos and Papavasiliou (2006) [8] performed a comprehensive monitoring and data analysis research study by using Falling Weight deflectometer (FWD) for in situ evaluation of recycled pavements. Proverbio and Venturi (2005) [9] evaluated the reliability of rebound hammer test and UPV test on concrete of different composition and strength. Rens et al. (2005) [10] explained application of NDE methods for bridge inspection, which is Bridge Evaluation Using NDT (BENT). Malavar et al. (2003) [11] used pull off tests to evaluate effects of temperature, moisture, and chloride content on CFRP adhesion. Pascale et al. (2003) [12] carried out an experimental program involving both destructive and nondestructive methods applied to different concrete mixtures, with cube strength varying from 30 to 150 MPa, to define a relation between strength and parameters. Tests performed are pulse velocity, rebound hammer, pull out, and probe penetration, microcoring and combined methods. Almir and Protasio (2000) [13] used NDT methods to determine the compressive strength of concrete relationship between the measured mechanical or physical properties and the strength and also presented the validity of pull off, pin penetration, and UPV for assessing the concrete strength. Chen et al. (1995) [14] presented findings of research on fiber optic bragg gratings as stress/strain sensors for monitoring the critical sections of composite beams.

Several researchers performed different types of NDT tests such as mechanical, chemical, electrochemical, and magnetic methods to evaluate the condition by combining the results. Rens and Kim (2007) [15] inspected a steel bridge using several NDT methods such as visual inspection, hammer sounding, Schmidt hammer, and UPV testing including tomographic imaging; results of NDT had been used to determine areas, to be tested with local destructive tests such as compressive strength, chloride testing, and petrographic testing. Magnetic concrete cover meters are widely used to estimate the cover to steel bars. Bhadauria and Gupta (2007) [16] presented case study of deteriorated water tanks situated in the semitropical region of India. Parameters measured are concrete cover, carbonation depth, chloride concentration, compressive strength, and so forth. NDT methods used are cover meter, Phenolphthalein indicator test, Quantab test, Potentiometric Titration, Schist's hammer test, and UPV test. Amleh and Mirza (2004) [17] performed concrete cover test, Half cell Potential, corrosion rate, electrical resistivity, chloride content at steel level (%), steel bar mass loss (%), absorption, pulse velocity, compressive strength, carbonation depth, petrographic examination, and permeability test. Dias and Jayanandana (2003) [18] used nondestructive techniques of visual inspection, perusal of drawings, ultrasonic pulse velocity measurements, cover-meter surveys, and core testing for the condition assessment; parameters required for evaluating the durability had been identified as (1) depth of carbonation; (2) cover to reinforcement; (3) chloride content; and (4) sulfate content. Bruhwiler and Mivelaz (1999) [19] highlighted the findings of two studies (i) investigated chloride ingress under given climatic conditions and in situ evaluation of concrete cover, (ii) used numerical models to investigate the effects of early age cracking and also determines preventive measures to be taken to limit the development of cracks.

Propagation of waves or reflection of different rays such as X-ray, through concrete structures, can be used to detect the deterioration level of concrete structures. Impact echo method has been used by many researchers to evaluate the condition of concrete. In this method a spring loaded device is used to generate waves, and these waves are used to detect condition of structures. Kamal and Boulfiza (2011) [20] assessed penetration of alkalis using X-ray mapping of backscattered electron images (BEI) and crosschecked by line and point energy dispersive spectroscopy (EDS) techniques. Shiotani et al. (2009) [21] used Acoustic Emission (AE) technique to evaluate the structural condition of a concrete bridge. Cascante et al. (2008) [22] presented a methodology for the ND evaluation using the multichannel analysis of surface waves (MASW).

Zhu and Popovics (2007) [23] applied air coupled impact echo (IE) for NDE of concrete structures; air couple sensor is a small (6.3 mm dia.) measurement microphone located several cms above the top surface of the concrete being evaluated. Results show that air-coupled sensors are effective for IE tests. Nachiappan and Cho (2005) [24] analyzed corrosion products using X-ray diffraction and atomic absorption spectroscopy to find mineral present in them. Gibson and Popovics (2005) [25] proposed a new approach for NDE of concrete structures based on guided wave theory "Impact Echo resonance in plates corresponds to the zero-group-velocity frequency of the S1 lamb mode." Akuthota et al. (2004) [26] presented the experimental results of using near field microwave NDT techniques for detecting disbond in a specially prepared carbon fiber reinforced polymer (CFRP) reinforced mortar sample. Gassman and Tawhed (2004) [27] presented the results of an NDE testing program performed to assess the damage in concrete bridge by using impact echo method. Paulson and Wit (2003) [28] described the use of acoustic monitoring system to manage concrete structures, by presenting two case studies. As concrete and steel both are excellent acoustic transmitters, this technique is useful for concrete structures. Grosse al. (2003) [29] described the use of signal-based acoustic emission techniques in civil engineering. Popovics et al. (1998) [30] reviewed one-sided stress wave measurement method in concrete. This method provides valuable information on the state of material, when access to only one side surface is possible, such as for the case of concrete pavements. Nagy (1997) [31] discussed a NDE method for determining "E" (Young's modulus) of concrete at very early ages, by measuring dynamic response frequency on concrete prism with Fourier Transform (FTT) analyzer.

Ground penetrating radar (GPR) is another method to locate the rebars, voids, and other defects in concrete structures. Chen and Wimsatt (2010) [32] used 400 MHz ground-coupled penetrating radar (GCPR) to evaluate the subsurface conditions of roadway pavements. Yehia et al. (2007) [33] studied the different NDE techniques used to assess the condition of concrete bridge deck. Experiments performed are infrared thermography, impact echo, and ground penetrating radar (GPR) to detect common flaws in concrete bridge decks. Maierhofer (2003) [34] presented the importance and limitations of ground penetrating radar (GPR) methods. Maser (1996) [35] discussed GPR technology that has been applied to the evaluation of pavements, bridge decks, abutments, piers, and other construction facilities to assess conditions and to evaluate damage and deterioration that develops over time.

Ultrasonic pulse velocity is used by many researchers for the assessment of concrete properties by using travel time of longitudinal waves over a known distance. Sharma and Mukherje (2011) [36] used ultrasonic guided waves for monitoring progression of rebar corrosion in chloride and oxide environment. Terzic and Pavlovic (2010) [37] applied NDT methods that is Image Pro Plus (IPP) and Ultrasonic Pulse Velocity (UPV), on the corundum and bauxite-based refractory concretes. Shah and Hirose (2010) [38] presented an experimental investigation of the concrete applying non-linear ultrasonic testing technique. Ervin et al. (2009) [39] created an ultrasonic sensing network to assess reinforcement deterioration. Guided ultrasonic waves had been used to monitor reinforced mortar specimens under accelerated uniform and localized corrosion. Stergiopoulou et al. (2008) [40] presented a procedure for NDT of urban concrete infrastructures using UPV measurements and applied to concrete garages. UPV has been used as an indicator of concrete quality. Yoshida and Irie (2006) [41] proposed a macroscopic ultrasonic method, which allows measurement of concrete thickness, crack width, and characteristics using the concrete surface sonic speed. Dilek (2006) [42] discussed the use of pulse velocity, Young's modulus of elasticity, and air permeability of concrete to evaluate the extent of damage of a concrete. Abo-Quadais (2005) [43] conducted an experimental study to evaluate the effects of concrete aggregate degradation, w/c ratio, and curing time on measured UPV. Equipment used in this study was the portable ultrasonic ND digital indicating tester (PUNDIT). Lee et al. (2004) [44] used UPV methods for determining setting time of concrete especially high-performance concrete (HPC). Shah et al. (2000) [45] described laboratory-based NDE techniques based on measurements of mechanical waves that propagate in the concrete. Ultrasonic longitudinal wave (L-wave or P-wave) signal transmission measurements have been applied to detect the present of damage in the form of distributed cracking in concrete. Davis et al. (1997) [46] introduced several NDE techniques including UPV, impulse response, parallel seismic, and cross-hole sonic logging for evaluating concrete quality of hazardous waste tanks. Rens and Greimann (1997) [47] presented the concept and application of using ultrasonic continuous spread-spectrum signal for monitoring and identification of deteriorating infrastructure. The new ultrasonic NDE method called direct-sequence spread-spectrum ultrasonic evaluation (DSSSSUE) is now being developed.

Several NDT methods utilize electrical properties of concrete structures to assess the condition of structures. El-Dakhakhni et al. (2010) [48] developed a technique based on local dielectric permittivity for detecting ungrouted cells in concrete block masonry constructions, and this has been used to design coplanar capacitance sensors with high sensitivities to detect construction defects. Nassr and El-Dakhakhni (2009) [49] presented in situ NDE technique using Coplanar Capacitance Sensors (CCSs) to detect variation of material dielectric for damage detection in FRP-strengthened concrete structures and also described several NDE techniques such as radiography, ultrasonic testing, and infrared thermography. Rajabipour et al. (2005) [50] discussed the interpretation of electrical conductivity measurements in concrete to assess water penetration. Liu et al. (2002) [51] developed a non-destructive evaluation technique, time domain reflectometry (TDR) that is capable of determining the location and severity of corrosion of embedded or encased steel rebar and cables.

Electrochemical methods are also developed and used by many researchers to detect the deterioration level of structures. Sangoju et al. (2011) [52] studied the corrosion behavior of steel in cracked Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC) concretes by measuring chloride ion penetrability, sorptivity, half-cell potential, resistivity, total charge passed, and gravimetric weight loss. So and Millard (2007) [53] discussed a method for rapid assessment of the corrosion rate of reinforcing steel in concrete structures by measuring transient potential response using galvanostatic pulse perturbation. Corrosion rate calculated has been compared with the corrosion rate obtained from linear polarization resistance (LPR) method. Parthiban et al. (2006) [54] carried out potential surveys on the concrete structures. Among all electrochemical methods potential measurement is the mostly used field technique for detecting corrosion activity in steel. Bola and Newtson (2005) [55] selected five sites for field evaluation of reinforcement corrosion, permeability, chloride ion concentration, half-cell potential, polarization resistance, and pH value. Corrosion is evaluated by half-cell potential measurements, polarization resistance measurements, and visual inspection of bars. Bavarian and Reiner (2004) [56] applied electrochemical monitoring technique on samples immersed in 3.5% NaCl solution, to monitor corrosion behavior. McCarter and Vennesland (2004) [57] presented a review of sensors and associated monitoring systems used to evaluate corrosion activity, concrete resistivity, oxygen availability, carbonation, and chloride ingress within a structure. Pal et al. (2002) [58] investigated the rate and amount of corrosion of steel in concrete. Tests performed for analyzing corrosion are half-cell potential, potentiodynamic, accelerated electrolytic corrosion tests, and accelerated carbonation test. Costa and Appleton (2002) [59] described a series of case studies of different types of concrete structures, subjected to harsh marine environment that deteriorated due to chloride-induced corrosion. Tests performed for indepth inspection are chloride content, electrical resistivity, and half-cell potential using Ag/AgCl electrode. Klingoffer et al. (2000) [60] developed a nondestructive polarization technique for RC structures called as galvanostatic pulse method. Bjegovic et al. (2000) [61] described the electrochemical and nonelectrochemical methods of determining corrosion rate of concrete. Carnio (1999) [62] presented study of three electrochemical NDT methods to investigate the status of corrosion in RC members half-cell potential, concrete resistivity, and polarization resistance.

Vibration-based techniques can be used to monitor the concrete structures. Bagchi et al. (2010) [63] applied cost effective and easy to implement, vibration-based damage identification (VBDI) techniques for Structural Health Monitoring of a bridge, based on changes in the dynamic characteristics of a structure to determine the location and extent of damage in the structure. Hsieh et al. (2006) [64] described the use of vibrational monitoring in the field of structural analysis for detecting and locating structural damage for the purpose of structural health monitoring. Ma et al. (2005) [65] proposed a method of detecting, locating, and quantifying structural damage by measuring structural vibrations. In this study, damage has been assumed to be represented by change in stiffness. For monitoring the health condition of a civil infrastructure before or after seismic event, various methods have been developed such as Lamb wave and eddy current.

Permeability or porosity of concrete structures is responsible for the diffusion of harmful agents in the concrete. Deo et al. (2010) [66] evaluated volumetric porosity by image analysis and hydraulic conductivity by a falling head permeability cell. Durham et al. (2007) [67] examined the causes of longitudinal cracking deterioration by performing investigation such as site bridge inspections, determining live load positions, testing for concrete permeability, collecting local relative humidity data, and determining the in situ moisture content of the beams. It is important to determine near surface characteristics of concrete which promotes the ingress of gases or liquids containing dissolved contaminates. McCarter et al. (2001) [68] presented the arrangements of Covercrete sensors for in situ monitoring of cover zone properties. Lampacher and Blight (1998) [69] investigated oxygen permeability and water sorption for the inservice structures of 20–30 years age. Al-qadi et al. (1997) [70] conducted an experimental program to study the effect of chloride contamination of Portland cement concrete (PCC) on its complex permittivity over low radio frequency (RF) range (0.1 – 40.1 MHz). Classie et al. (1997) [71] studied test to obtain absorption and sorptivity of cover concrete and modeled them by equation of capillary suction and permeability. Tests performed are initial surface absorption test (ISAT), Covercrete absorption test (CAT), and the sorptivity test. Blight and Lampacher (1995) [72] described the results of an investigation on the use of Covercrete absorption test (CAT) as an in situ technique for assessing the near surface permeation properties of concrete.

3. Available NDT Methods for Evaluating RC Structures

NDT methods for assessing the concrete structures have been classified by many researchers based on the governing principle. McCann and Forde (2001) [4] described five types of NDT methods: sonic/ultrasonic, electromagnetic methods, electrical methods, infra-red thermography, and radiography. Rens et al. (1997) [1] discussed five different types of NDT techniques: acoustic emission, thermal methods, ultrasonic methods, magnetic methods, and vibration analysis. Maierhofer et al. (2010) [73] discussed deterioration mechanisms of reinforced concrete structures with standard testing methods such as microscopic examination of concrete, determination of chloride content. Maierhofer et al. (2010) [74] discussed planning and implementation of NDT methods for structural health monitoring and reviewed several methods including wireless monitoring, electromagnetic and acoustic waves, magnetic flux leakage, electrical resistivity, and measuring corrosion rate. Successful use of NDT methods required good knowledge of principles, advantages, and limitations of methods. Different NDT methods and parameter measured by it have been presented in Table 1.

4. Various National and International Codes Accepting NDT Methods

Several national and international codes of practice accepted and include the NDT methods: List of tests and different codes accepting the test methods are shown in Table 2.

5. Discussion

An NDT method provides indirect results which can be related to various properties of concrete structures. In the last few decades NDT methods have been developed form

Table 1: Different NDT methods and parameter measured.

S. no.	Parameter measured	NDT method	Advantages	Limitations	Principle
1	Concrete quality, cracks, defects, and voids	Visual inspection	Rapid, economical	Expertise is required, superficial, and depends upon skill of viewer	Based on the visual defects on the surface
		Image Pro Plus (IPP)	Simple, rapid, cheaper	Slow results	Comparing colors of different objects
		Acoustic emission (AE)	Fast results, detect changes in materials	Costly, defects already present are not detected	Sudden distribution of stresses generates elastic waves
		Impact echo	Able to detect condition of concrete accessible from one side only, quick, accurate, and reliable	Interpretation is difficult, reliability decreases with increase in thickness, and accuracy depends on impact duration	Transmission and reflection of electromagnetic waves
		Infrared thermography	Easy interpretation, simple, safe, no radiation, rapid setup, and portable	No information about depth or thickness of defects, and results affected by environmental conditions	Surface temperature variation
		One-sided signal wave transmission measurements	Used to detect structures accessible from one side only such as pavements	Large thickness affects the results	Propagation velocity of signal waves
		Impulse response	Simple, easy to handle	Depends on the skill of user, and deep damages influence the results	Based on stress wave test method
		Radiography	Thickness and composition can be easily detected, and rebars can be located	Expensive, hazardous, and limited to low thickness	Velocity of X and gamma rays and its attenuation
		Petrographic testing	Provides information about alkali-silica reaction, alkali carbonation reaction, sulfate attack, freezing, and thawing	Required high skill for the interpretation of result	Samples are examined through a petrological microscope using reflected or transmitted light
		Lamb Wave Theory (LWT)	Relatively accurate	Difficult interpretation	Based on guided wave theory
2	Compressive strength, surface hardness, adhesion	Rebound hammer	Simple, quick, and inexpensive	Not so reliable, smoothness, age of concrete, carbonation, and moisture content can affect results	Rebound of plunger when strucked with concrete indicates strength
		Ultrasonic pulse velocity (UPV)	Quick, portable, large penetration depth, Simple interpretation, and moderate cost	Not very reliable, moisture variation and presence of reinforcement can affect results	Ultrasonic wave velocity and its attenuation
		CAPO test	Correlation between pull out force and compressive strength is reliable	Damage to the surface	Expanded ring in the cored hole is pulled out
		Probe penetration	Simple, needs less training, and low maintenance	Leave a hole in concrete surface, and coarse aggregates affect the penetration	Penetration of probe is measured and related to strength
		microcoring	Good correlation between test results and compressive strength	Depends on the preparation of specimens	Extraction of microcore samples from a concrete structure is used for analysis
		Pull off test	Fast results, evaluate adhesion, and tensile strength which can be converted to compressive strength	Damage to the surface	A disc is bonded to the testing surface, and when disc is pulled off, force required is used to obtain pull off strength

Table 1: Continued.

S. no.	Parameter measured	NDT method	Advantages	Limitations	Principle
3	Chloride concentration	Quantab test	Fast and accurate	Expensive, hazardous, limited to low thickness	Reaction of silver dichromate with chloride ion produces white column on the strips
		Potentiometric titration	Reliable	Requires skilled personal	Using acid or water soluble methods, the final volume will indicate chloride content
		Rapid chloride test	Portable, simple, and quick	Variation in results by the presence of certain materials	Potential difference of unknown solution is compared with potential difference of solutions with known chloride concentration
4	Corrosion rate, percentage of corrosion, corrosion progress	Galvanostatic pulse method	Measures half-cell potential and electrical resistance simultaneously	Unstabilized readings	Based on the polarization of rebar by means of small constant current
		Linear polarization resistance (LPR)	Rapid, requires only localized damage, more detailed information	Measurements are affected by temperature and humidity	Electrical conductivity of fluid can be related to its corrosiveness
		Half-cell potential	Simple, portable, results in the form of equipotential contours	Needs preparation, saturation required, not very accurate, and time consuming	Electric potential of rebars is measured relative to half cell and indicates probability of corrosion
		Time domain reflectometry (TDR)	More robust, easy, locates corrosion, and identifies extent of damage	Less sensitive	By applying a sensor wire along side of the reinforcement a transmission line is created. Physical defects of the reinforcement will change the electromagnetic properties of the line
		Ultrasonic guided waves	Identifies location and magnitude of corrosion	Not very reliable	Based on propagation of ultrasonic waves
		X-Ray diffraction and atomic absorption	Simple and reliable	hazardous	Intensity of X-ray beams reduces while passing through a material
5	Carbonation depth, pH of concrete	Phenolphthalein indicator test	Simple, quick, and inexpensive	Inappropriate for dark aggregates, results affected by saturation	Carbonation reduces pH of the concrete
		Rainbow indicator	Quick, descriptive, and easy to use and interpret	Requires drilling of concrete surface up to rebar depth	Carbonation reduces pH of the concrete
6	Pavement inspection and subsurface condition	Ground-coupled penetrating radar (GPR)	Low cost, portable, effective	Complex results, difficult interpretations	Propagation of radiofrequency (0.5 to 2 GHZ)
		Hammer sounding	Simple, easy to handle	Depends on the skill of user, and deep damages influence the results	Surface is striked with hammer and hollow or dull tone indicates the existence of delamination
		Acoustic tomography	Useful results, moderate	Requires skill, high cost	Waves were received on opposite side, and wave velocity depends on material properties
		Falling weight deflect meter (FWD)	Useful results	Can provide misleading results and requires experience for interpretation	Load is produced by dropping a large weight to detect concrete
7	Flaw detection inside decks, delamination, location, and extent of damage in bridges	Chain drag	Simple, portable	Time consuming, tedious	Chain is dragged over surface for flaw detection
		Vibration based damage identification (VBDI)	Easy to implement, cost effective	Environmental factors, errors in measurements, and nonunique solutions	Based on changes in the dynamic characteristics of a structure

Table 1: Continued.

S. no.	Parameter measured	NDT method	Advantages	Limitations	Principle
8	Entire depth of damage, percentage of damage, identification of deteriorating infrastructure	Seismic refraction method	Calibration is not necessary, more reliable	Valid for high speed for large depths	Seismic waves travel outward from a source and reach a detector
		Ultrasonic longitudinal waves (L-wave, P-wave)	Inspect also at large depths	Not appropriate as primary investigation method	Transmission and reflection of ultrasonic waves
		Ultrasonic continous spread spectrum signal	Improved sensitivity	Difficult interpretation	Signals are received by detectors and signal speed depends on defect
9	Permeability, water absorption	Water permeability test	Preparation and skill required, time consuming	Semidestructive type test	Assesses the ease with which water penetrates in concrete
		Initial Surface Absorption Test (ISAT)	Consistent results in laboratory	Problems in using in situ, affected by increase in temperature	Rate at which water is absorbed in concrete is measured
		Covercrete absorption test (CAT)	Not influenced by local surface attacks	Sensitive to W/C ratio, curing time and moisture content	Rate of absorption of concrete is measured
10	Concrete cover, rebar diameter, location of reinforcement	Cover meter	Portable	Slow, affected by deep cover and closely spaced bars	Electromagnetic induction
		Radioactive methods	Simple	Hazardous	Generates images of the structure of RC and steel
13	Load bearing capacity of bridge	Static truck load test	Reliable	Dangerous	Response of strain sensors under truck load indicates load bearing capacity
14	Relative conditions of brick masonry side walls	Multichannel Analysis of Surface Waves (MASW)	Reliable, fast and economical	Expensive, time consuming	Uses multiple sensors to record wave field
15	Detecting disbands	Microwave NDT method	Detects from one side, rapid, noncontact, and robust	Costly	Reflection and transmission coefficients are measured and related to material properties
18	Stress/strains sensor for monitoring composite beams	Fiber optic Bragg grating sensors	Suitable for long-term tests	Slow response	Monitors the response of structure subjected to full load

Table 2: Different codes describing NDT methods.

S. no.	Tests/parameters	Codes
1	Alkali aggregate reactivity	IS 2386 (Part 7): 1963
2	Petrographic examination	IS 2386 (Part 8): 1963, ASTM C856-77
3	Pull out test	IS 2770: 1967, ASTM C900-94, E DIN EN 12399 (July 1996), ISO/DIS 8046
4	Water soluble chlorides in concrete admixtures	IS 6925: 1973
5	Ultrasonic pulse velocity	IS 13311 (Part 1): 1992, ASTM C597-97, BS 1881: Part 203: 1986, BS 4408: pt. 5, NDIS 2416-1993
6	Rebound hammer	IS 13311 (Part 2): 1992, ASTM C805-97, BS 1881 Part 202: 1986, EDIN EN 12398 (1996), ISO/CD 8045
7	Abrasion resistance	IS 9284: 1979, ASTM C779-76, ASTM C944-80
8	Permeability	IS 3085: 1965
9	Testing drilled cores	ASTM C 42-87
10	Infrared thermography	ASTM D4788-88
11	Ground penetrating radar	ASTM D6087-97
12	Density by nuclear methods	ASTM D2950-91, ASTM C1040-93
13	Impact echo method	ASTM C1383-98a
14	Half-cell potential	ASTM C876-91
15	Penetration resistance	ASTM C 803-82
16	Dynamic modulus of elasticity by electromagnetic methods	BS 1881: Part 102:1983
17	Radiography	BS 1881: Part 205: 1970, BS 4408: pt. 3, NDIS 1401-1992
18	Water absorption	BS 1881: Part 122: 1983, AS 1012.21-1999
19	Electromagnetic covermeter	BS 1881: Part 204: 1986, BS 4408: pt. 1
20	Concrete strength by near to surface methods	BS 1881: part 207: 1992
21	Strain gauges for concrete investigation	British Standard Institution, London, 1969, (83)
22	Density with gamma rays	TGL 21 100/01
23	Determination of chloride and sulfate in hardened concrete	AS 1012.20-1992
24	Visual inspection	NDIS 3418-1993
25	In situ monitoring of concrete	NDIS 2421-2000
26	Surface hardness method	BS 4408: pt. 4

rebound hammer to new sophisticated techniques based on propagation of waves in the concrete. With the development in software technologies and battery operated small computers, NDT methods are getting popular among researchers and engineers for quick evaluation and interpretation of results. In the future NDT methods can be useful for the various purposes such as for identifying deterioration levels and modeling the life of structures, extracting indepth information about material properties, and developing methods for combining the results of different NDT methods for better evaluation of condition of concrete structures.

Combining several methods for assessing the structures is now required for better assessment. Normally an NDT engineer uses single method for evaluating a parameter, but sometimes combining several methods for better assessment has been required. So to use and combine different methods knowledge about principle, advantages and limitations of different available methods are required by engineers. Combination of several methods has been required to strengthen the results of each other. Several properties of structures can affect the same measurement, and it is difficult to distinguish the effect of each property on a measurement. Based on experience and knowledge the better combination of NDT techniques can be selected for the diagnosis of concrete structures.

NDT methods inspect or measure without any harm to the structure; no damage of specimens is required during testing. It can be applied for inservice inspections, and this is major advantage of NDT methods, and they are capable of detecting flaws and defects early. By using NDT methods very precise assessment of the defect extent can be evaluated, and when combined with laboratory tests they give good results. Also they are capable of monitoring structures continuously.

NDT results are complex and provide detailed information for concrete tested. It has been difficult for the engineers to understand the results of NDT, and so expertise and experience are required for handling NDT equipments and for the interpretation of results. Sometimes results are not satisfactory, due to wrong selection of method or equipment, so training is a must for using NDT. If assumed physical condition of structure is different from real condition then results and its interpretation are not as expected.

6. Conclusions

Various NDT methods based on different principles, with their individual merits and limitations, have been discussed. It has been recognized that NDT plays an important role in condition assessment of existing structures, and there has been an urgent need for developing standards for performing NDT methods and for interpretation of NDT results.

Major advantage of NDT methods has been recognised as their capability to test in situ. Great deal of expertise is required for interpretation of NDT field observations and test results. NDT provides useful information by revealing hidden or unknown defects, and repair or replacement of RC structures can be planned according to NDT results. Combination of different NDT methods available is a better way to assess the structures.

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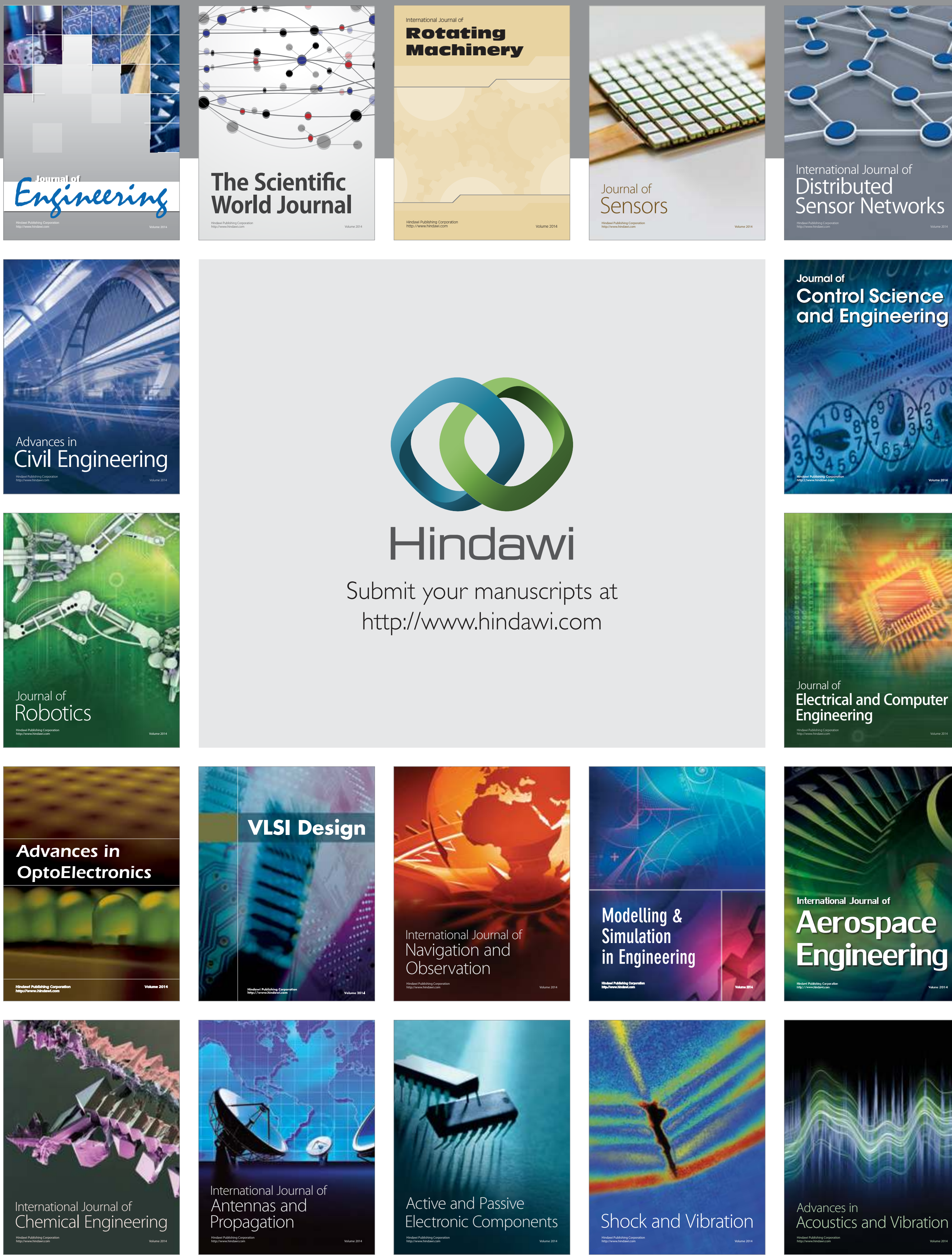
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