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Non-Destructive Testing Techniques for Condition Assessment of Concrete Structures: A Review

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Abstract

Non-destructive testing (NDT) techniques have developed as important instruments in the evaluation of concrete structures, providing a way to analyze structural integrity and material qualities without causing damage. In analyzing the uniformity, homogeneity, approximate compressive strength, durability, the level of rebar corrosion in concrete, and other properties of damaged buildings, NDT technologies have a significant benefit. This paper offers a thorough examination of several NDT methods, emphasizing their usefulness in finding internal flaws, locating embedded items, and measuring surface-hardness and in-situ stress. Each method's applicability, limitations, and measured parameters are thoroughly addressed. The criteria for selecting appropriate NDT methods are discussed, followed by a comparison of different approaches to facilitate decision-making. The interpretation of NDT results is discussed, highlighting the significance of precise data processing and the relevance of sophisticated technology. Case studies were also provided to demonstrate the actual implementation and efficacy of NDT techniques in real-world circumstances. The assessment also suggests investing in advanced data visualization tools to better the interpretation and sharing of NDT results, as well as combining NDT data with Building Information Modeling systems to provide a more complete picture of structural problems. Finally, the paper indicates that NDT techniques are critical for assuring the safety, durability, and preservation of concrete structures, thereby significantly contributing to the upkeep of our built environment.

Keywords

Flaws, NDT, In-situ Stress, Surface-Hardness

1. Introduction

Assessing the service life of structures is a crucial aspect of modern structural engineering. The longevity of a structure is influenced by its design, construction, aging, and maintenance. On-site diagnostics of concrete structures are essential for engineers to make informed decisions about the condition of both new, existing and damage structures. This is important for several reasons, including safety, compliance with updated codes and standards, longevity and maintenance, performance evaluation, economic considerations, and historical preservation. Traditionally, the quality of concrete in civil structures is evaluated using concrete cylinder samples from a project, which are tested through simple compression tests as outlined in the ASTM Standard C39 [13]. However, this method requires a large number of samples and direct measurement with destructive tests, which can be expensive and time-consuming. Additionally, these

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methods have several drawbacks, such as delayed results, potential differences between the concrete in specimens and the actual structure, and the influence of specimen size and shape on strength properties. To address these limitations, a more prevalent alternative strategy is to combine direct compressive testing with advanced non-destructive tests (NDT). This approach offers a more efficient and accurate assessment of concrete quality without the need for extensive sampling and destructive testing.

Non-Destructive Testing (NDT) refers to methods used to examine objects, materials, or systems without affecting their future usability. This means inspecting or measuring without causing any harm [14]. The tests available for structures range from completely non-destructive, which cause no damage to the concrete, to those that slightly, damage the surface, and partially destructive tests like core tests and pullout tests, which require surface repair afterward. NDT methods are crucial in any investigative program because they allow for the collection of valuable information. They serve two primary purposes in diagnosing concrete structures [15, 16]: a) Estimating Mechanical Properties and Assessing Conditions: This includes evaluating the strength and overall condition of the structures [17-19]; b) Assessing Safety and Stability Markers: This involves checking for factors such as porosity, depth of carbonation, water content, discontinuities, and weaknesses [20-22]. NDT is increasingly seen as a powerful tool for analyzing structures. Its popularity is growing due to its reliability and effectiveness, making it a preferred choice over traditional random sampling methods for material analysis.

There are various NDT techniques based on different principles, which can be categorized as acoustic, optical, electromagnetic, thermal, or radiographic [23]. Numerous NDT methods have been developed to evaluate concrete structures, the most common modern building material. However, assessing historic structures presents unique challenges. The primary materials used in these structures vary widely, making it essential to understand old raw materials, their technological processes, and chemical changes to assess past masonry accurately [24]. According to Forde et al. [25], five major factors must be considered in an NDT survey: the required depth of penetration, the necessary vertical and lateral resolution, the contrast in physical properties between the target and its surroundings, the signal-to-noise ratio for these physical properties, and historical information about the construction methods used in the structure. Modern condition evaluation techniques can assess structures or structural elements for varying levels of damage [24]. These methods have been used for over three decades to evaluate the state of structures. The choice of an NDT technique depends on several factors, including the required structural parameters, the feasibility of the test procedure, and the cost of procuring test equipment. Therefore, NDT methods are versatile tools used to evaluate the integrity of both new, existing and damage structures.

For new structures, the primary applications of NDT are expected to be in quality control (QC) and quality assurance (QA) processes, helping to identify any defects or inconsistencies in materials and components early on. These methods help eliminate uncertainties about the acceptability of the supplied material, reduce concerns about workmanship in concrete production, and monitor strength development related to formwork removal, curing completion, and structural changes. This proactive approach prevents potential issues down the line [26]. Additionally, this methods help to verify the dimensional accuracy of components, which is especially important in complex assemblies where precision is key [27]. Furthermore, NDT ensures that new structures comply with industry standards and regulations, which is essential for safety and legal reasons, and often a prerequisite for project approval and certification.

Evaluating existing structures using NDT is essential for extensively to monitor the condition of structures over time, ensuring they remain safe and functional. The process examines the potential durability of the concrete, monitoring long-term changes in its properties to inform maintenance strategies [28]. Additionally, assessments provide detailed information for proposed changes in use, insurance, or ownership, highlighting specific issues that influence decisions about the structure’s value and safety. Overall, the application of NDT in existing structures is a comprehensive approach that enhances safety, extends the lifespan of structures, and reduces maintenance costs by allowing for timely and targeted interventions [29].

Non-Destructive Testing (NDT) methods are crucial for evaluating and managing damaged structures, focusing on identifying internal flaws such as cracks, voids, or delamination that are not visible on the surface [30]. When structures are damaged by natural disasters, accidents, or wear and tear over time, NDT provides a thorough assessment of the extent and nature of the damage. For structures affected by corrosion, NDT methods are used to locate and assess the severity of corrosion in steel reinforcements, which is vital for maintaining the structural integrity of bridges, buildings, and other infrastructure. Additionally, NDT verifies the effectiveness of repairs and retrofits, ensuring that any interventions have successfully restored the structure’s integrity and performance.

NDT methods provide valuable understandings; their accuracy and consistency can vary significantly. Factors such as the quality of the equipment, the skill of the operator, and the specific conditions of the concrete being tested can all influence the results. However, the accuracy of measurements in the condition assessment of concrete can be achieved in different ways. First, ensure that NDT equipment is properly calibrated using known reference standards to minimize systematic errors, and validate the NDT methods against destructive testing methods like core sampling to establish a correlation between NDT results and actual concrete properties [31, 32]. Combining multiple NDT techniques is the other way to achieve accuracy, such as SonReb techniques, can improve accuracy by leveraging the strengths of each method [33-36]. Statistical analysis of the collected data, including calculating the mean, standard deviation, and confidence intervals, helps determine the reliability and accuracy of the measurements. Additionally, utilizing artificial intelligence and machine learning algorithms to analyze NDT data can identify patterns and correlations that might not be evident through traditional analysis, further improving the accuracy of condition assessments [37]. By following these steps, the accuracy of NDT measurements can be significantly enhanced, leading to more reliable assessments of concrete structures.

The aim of this review is to provide a comprehensive understanding of various techniques, their principles, and applications, helping to select the most suitable methods by identifying each technique’s strengths and limitations for accurate evaluations of new, existed and damaged structures. It structured into seven sections, it begins with a Literature Review of NDT research, followed by International Standards for NDT, details NDT techniques and their effectiveness in the Assessment Methods section, explores advancements in Discussion, and concludes by highlighting the importance of NDT for structural safety and durability.

2. Literature Review

A vast number of studies have been conducted around the world to investigate the degradation of existing and new structures. When it comes to completing indirect assessments of concrete and masonry qualities, nondestructive procedures are quite important. Researchers worldwide presented their study on non-destructive evaluation techniques and potential strengthening measures that may become available from time to time for new, aging and deteriorating structures in diverse regions.

Numerous studies have been conducted on concrete utilizing mechanical based non-destructive testing (NDT) methods, highlighting their critical role in assessing the material properties. Many studies, such as those by, Shariati et al. [7], Sanchez et al. [38] and Kazemi et al. [9], have demonstrated the effectiveness of the Schmidt rebound hammer test in estimate compressive strength. These studies highlight the tests reliability and ease of use in various concrete structures scenarios. Likewise, research by Brencich et al. [39, 40] and Balla et al. [41] has extensively explored the application of Schmidt hammer test for assessing the mechanical properties of masonry structures. These studies provide valuable insights into the mechanical properties of masonry structures. Additionally, several studies, including those by Breccolotti et al. [34] and Bonagura et al. [33] have focused on combining multiple NDT methods, such as the SonReb techniques, to improve the accuracy of concrete evaluation. Alyamac et al. [42] and Kog [43] conducted studies that employed the Windsor Probe method to assess the in situ compressive strength of existing concrete structures. These researches contribute to a better knowledge of concrete's mechanical properties.

Other mechanical procedures for ensuring the integrity and longevity of concrete structures include pull-off and flat-jack testing. Consider a study conducted by Fazli et al. [44], Ramos et al. [45] and Bonaldo et al. [46] demonstrated the utility of the pull-off testing for assessing the interfacial bond strength between concrete and fiber reinforced concrete interface. Sadowski et al. [47] confirmed the reliability of this method to assess the failure mechanism of repair mortar-stone interface. Similarly, Mazzuca et al. [48] further validate this method reliability by characterizing mechanical properties of steel – reinforced grout for strength to strengthen the existing masonry and concrete structures.

A significant body of research has focused on the application of electromagnetic based non-destructive testing methods to evaluate concrete structures. For example, Solla et al. [49], Lombardi et al. [50] and Martini et al. [51] highlighted the effectiveness of the ground penetrating radar (GPR) test to characterize stone masonry and gather information on related mechanical properties. Alani et al. [10] discuss the use of GPR in two case studies. Forth Road Bridge in Scotland, which may have structural flaws such as fractured rebar and moisture infiltration at bridge surface and Pentagon Road Bridge in England may have faults such as structural cracks in the deck structure and deciding the arrangement of the upper and lower rebar placements across the bridge. Beben et al. [52] confirmed its reliability on reinforced concrete (RC) viaduct beams to determine the geometric characteristics of the beams, the spacing of reinforcing bars, and the depth of their location. While others researchers, [53-55] extensively investigating the application of Half-cell potential measurements for the assessment of the durability of reinforced concrete members where reinforcement corrosion is suspected. Similarly, Kim et al. [56] used the Half-Cell Potential Test method in their experimental tests to analyze cracks in concrete exposed to chloride attack, taking into account the impacts of water-cement ratio, fracture width, and cover depth. Additionally, several studies, including those by Lai et al. [35] and Rhazi et al. [36] Explored the benefits of combining multiple NDT methods, such as the Half-cell potential measurements and ground penetrating radar (GPR), to enhance evaluation accuracy in assessing corrosion in reinforced concrete.

Wave propagation or X-ray reflection through concrete or masonry constructions can be utilized to diagnose structural damage. Many research on concrete and masonry employed radiography to assess the state of structure has been extensive and varied. Kamal and Boulfiza [57] showcased the effectiveness of X-ray mapping of backscattered electron images (BEI) and energy dispersive spectroscopy (EDS) techniques to determine whether glass fiber-reinforced polymer (GFRP) rebar’s allowed water to penetrate, while blocking alkalis. Zhang et al. [58] employ an advanced non-destructive technology called neutron radiography to visualize water movement into concrete and other cement-based composites, as well as to measure time-dependent moisture distributions. De Beer et al. [59] confirmed the reliability of neutron radiography capability to obtain quantitative data for porosity and sorptivity in concrete to laboratory or conventional measurements, while Pei et al. [60] carried out experimental simulation to use high-energy X-ray system on-site to enhance image by reducing noise properties to inspect reinforced concrete structures. Additionally, Movafeghi et al. [61] integrated Radiography and Weighted Nuclear Norm Minimization method to inspect and monitoring the concrete structures by improving visualization of reinforcement bars, fittings or tension cables and defects of concrete.

Over the years, numerous studies employ ultrasonic based testing to examine concrete and masonry structures by measuring the transit duration of longitudinal waves over a given distance. For instance, Bogas et al. [62] and Mata et al. [31] highlighted the effectiveness of the ultrasonic pulse velocity test in estimating concretes compressive strength. Yang et al. [32] further validate this methods reliability across various construction scenarios. Lee et al. [63] employed UPV methods to determine the setting time of concrete and mortar for different water-to-cementitious materials (w/cm) ratios and with and without fly ash during the first 24 hours of age. Huang et al. [64] explored the benefits of combining multiple NDT methods, such as the UPV and hammer test, to enhance evaluation accuracy of compressive strength. Additionally, Kewalramani et al. and Trtnik et al. integrated UPV methods with artificial neural networks to improve predictive accuracy in concrete compressive strength. Lastly, the research by Manning et al. [65] Highlighted UPV to investigate the inner consistency of masonry walls and columns to determine the success of grout injection and the elasticity of masonry materials, while Valluzzi et al. [66] Investigated the reliability of this method in detecting in homogeneities in order to qualify diverse masonry conditions.

Krzemień et al. [11] create relationship between impact echo signals and concrete subjected to high temperature to study post fire mechanical properties of concrete. Similarly, Epasto et al. [67] investigated concrete degradation, temporal location, and energy content of harmonic components on fire-damaged concrete using impact echo methods and a wavelet time-frequency methodology. Kachanov et al. [68] investigated compact concrete building structures using a multiplicative impact echo method to determine the concrete strength both during the cement solidification process and while the building structures are operational. Another significant study by Sadri et al. [69] used ultrasonic based techniques of impact-echo method to assess the bonding condition between facing stones, mortar, and the inner rubble core, as well as the presence of voids and cavities in stone masonry. Lastly, the research by Zhang et al. [37] highlighted the advancement in integrating Impact-echo methods with advanced machine learning techniques for performing comprehensive analysis and pattern recognition of IE signals for full condition assessment (*i.e.*, defect detection, defect diagnosis, defect sizing and location).

Other ultrasonic based methods used for ensuring the integrity and durability of concrete structures include Acoustic Emission (AE) testing. Consider a study conducted by Noorsuhada et al. [70] and Yuyama et al. [71] showcased the effectiveness of the Acoustic emission test in fatigue damage assessment of reinforced concrete structures. Similarly, Elfergani et al. [72] conducted acoustic emission test for damage assessment of corrosion in pre-stressed concrete. Behnia et al. [73] and Tsangouri et al. [74] focused on structural helth monitoring of concrete structures. There are also research who used acoustic emission test to evaluate and monitor damage in masonry structures. For instance, Carpinteri et al. [75] and Wu et al. [76, 77] utilized acoustic emission test to detect damage in masonry structures. Additionally, Invemizzi et al. [78] prepared numerical model for the assessment of historical masonry structures and material monitored by acoustic emission.

Over the year, numerous studies have focused on the application of optical based non-destructive testing (NDT) methods to evaluate concrete and masonry structures. Yang et al. [79] Demonstrated the utility of 3D laser scanning technology in the generation and calibration of finite element model for health assessment of concrete structures. Law et al. [80] and Olsen et al. [81] used Terrestrial laser scanning for structural assessment of concrete. Whereas other studies focuses on visual inspection such as, Stewart et al. [82] Conducted visual inspection to validate its reliability for safety assessment of corroding reinforced concrete structures. Additionally, Patel et al. [83] Integrated visual inspection methods with machine learning aided robotic systems to automate visual inspection, which is important for both quality control and maintenance.

Many researchers use infrared thermography, which is another optical based non-destructive methods uses spectral analysis to evaluate the deterioration of concrete and masonry structures. Cheng et al. [84] used infrared thermography (IRT) to assess concealed flaws in various depths and regions of concrete by heating the embedded fault with lamps, followed by spectral analysis of the defect using elastic wave signals. Sirca et al. [85] evaluated the IRT for detecting flaws in concrete constructions. Lu et al. [12] focused on how the depth of delamination inside concrete pavement using the infrared thermography technique for bridge deck inspection. Omar et al. [86] examined the potential use of unmanned aerial vehicle (UAV) infrared thermography together with non-destructive testing technologies like hammer noises and half-cell potential testing to detect subsurface delamination in concrete bridge decks. Tavukçuoğlu et al. [87] used both active and passive infrared imaging techniques to detect degradation in masonry constructions. Cascardi et al. [88] report the findings of a big thermography campaign conducted in a cultural masonry building in southern Italy to determine the typologies of vaults covered in valuable frescoes for seismic vulnerability assessment. Lastly, Avdelidis et al. [89] provided an overview of infrared thermography and its applications in the evaluation of various traditional-historical materials and structures.

Several NDT approaches use concrete structures' electrical characteristics to assess their condition. Lataste et al. [90] The NDE technique was presented in the context of electrical resistivity measurements to parameters for detecting and locating fractures and spalling in concrete. Similarly, Ferreira et al. [91] suggested methodologies for predicting if concrete reaches a predetermined compressive strength before formwork removal. Lataste et al. [92] focused the utility of electrical resistivity measurement for the evaluation of the quantification of fiber orientation in steel fiber reinforced concrete (SFRC). Azarsa et al. [93] thoroughly investigated the link between concrete electrical resistivity and certain durability qualities. Yousuf et al. [94] carried out experiment to monitor the setting and hardening behavior of cement paste using electrical resistivity measurement. In addition, Araujo et al. [95] studied correlation between concrete strength properties and surface electrical resistivity. Lastly, Wang et al. [96] have studied the effect of moisture content on freeze–thaw behavior of cement paste by electrical resistance measurements.

Several researchers used various NDT technologies to monitor the concrete structures, such as strain sensing, computer tomography, and vibration-based methodologies. Ubertini et al [97] have proposed a novel use of cement-based nanocomposite technology for vibration-based structural health monitoring of concrete structures. Henault et al. [98] investigated mechanical behavior in RC structures by measuring strain and detecting cracks with a truly distributed fiber optic sensing system. du Plessis et al. [99] examined the use of X-ray computed tomography on concrete and asphalt building materials to better understand and improve their material properties for structural applications in civil engineering. According to Balázs et al. [100], X-ray CT can evaluate concrete structures and building materials in three dimensions, including aggregate size and distribution, pore or void size and distribution, freeze-thaw cycle deterioration, fire deterioration, and corrosion of steel pre-stressing wires. Zielińska et al. [101] Non-destructive tests were done using ultrasonic stress waves and computed tomography on intact masonry pillars with internal inclusions in the form of a hole, a steel bar grouted with gypsum mortar, and a steel bar grouted with cement mortar.

3. International Standards, Norms and Guidelines

Numerous technical publications by national and international authorities focus on methodical and scientific techniques for measuring the residual strength, durability, and reliability of structural materials, assemblies, and systems in existing structures. Given the complexities of concrete projects, these publications should be regularly evaluated, expanded, and improved. Standards serve as comprehensive guides, demonstrating proper approaches and procedures for identifying and evaluating flaws in materials and objects without causing damage. Consequently, various national and international technical organizations have developed standards for the mechanisms and applications of these technologies. From an engineer's perspective, these standards provide detailed guidelines that simplify the process of finding and evaluating defects in constructions, making them practical and easily applicable. This underscores the need for relevant technical agencies to conduct regular, legitimate experiments using innovative technology and equipment.

As illustrated in the Table 1, while some technical bodies have developed nationally acceptable or locally applicable standards for pre-investigation requirements and approved test procedures for a wide range of both classic and unconventional NDT techniques, others have lagged behind. American publications such as ASTM standards, British Standards (BS), and those from the International Organization for Standardization (ISO) provide comprehensive references and compilations of nondestructive testing standards. These include recommended equipment, evaluation procedures, test numbers, and methodologies for analysis and strength computation. However, the Ethiopian Standards Agency has not yet clarified the pre-investigation needs and test methodologies for even the most basic NDT techniques. Consequently, Ethiopian academics and professionals heavily rely on American and European standards to conduct NDT techniques. Additionally, the International Organization for Standardization (ISO) offers a broader range of NDT standards. Table 1 provides a list of international standards governing NDT techniques in civil engineering.

4. The NDT Assessment Method for Concrete Structures

Concrete became a popular building material around the world in the twentieth century, with reinforced cement concrete (RCC) constituting the majority of buildings built in the twentieth and twenty-first centuries. If properly constructed and positioned, these structures must withstand a wide range of climatic conditions over their lifetime. Non-destructive testing (NDT) is an important tool for evaluating these constructions because it may examine material qualities and identify potential problems without causing damage. This technology is becoming increasingly popular among researchers and engineers due to its capacity to quickly examine and interpret data without inflicting structural damage. Concrete can be inspected more precisely in stages depending on its structural importance and the quantity and quality of available data, even when the materials' strength classes are frequently unknown [102]. To prevent doubt about the structure's total resistance, evaluation techniques should strive to ascertain the real properties of building components with as much accuracy as feasible. This method is particularly useful for various reasons.

NDT helps to maintain the structural integrity of concrete, allowing for detailed investigation without affecting the concrete's physical state. This is significant for historical structures and critical infrastructure, which require the preservation of original materials. They also provide a full examination of concrete qualities, including compressive strength assessment, corrosion detection in reinforcement, permeability measurement, and crack and void identification. These examinations are critical for verifying that the concrete satisfies the specified specifications and finding potential flaws that could lead to structural failure. For example, early diagnosis of corrosion can prevent concrete from expanding and breaking, preserving its strength and durability.

Another key advantage of NDT is its impact on safety and reliability. NDT allows engineers to confirm that concrete structures are safe to use, which is critical for public safety. This is especially important for constructions like bridges, dams, and high-rise buildings, where a single failure could have disastrous repercussions. NDT technologies give reliable data on the condition of the concrete, allowing for informed judgments about essential repairs and maintenance [30]. Furthermore, early discovery of faults using NDT can result in prompt repairs, avoiding more extensive and costly damage in the future. Furthermore, NDT technologies are adaptable and can be used on both new and existing buildings. Because of their adaptability, they are useful instruments for continuous upkeep and evaluation, guaranteeing that structures stay in good shape for the duration of their lifespan.

From an economic and sustainability standpoint, preserving existing building stock is preferable to dismantling and replacing it. The evaluation step is critical in the decision-making process because it accurately examines, verifies, and maintains existing structures [103]. Advances in technological inspection, nondestructive techniques (NDT), structural health monitoring (SHM), and structural analysis of concrete structures, combined with modern reuse and sustainability requirements, as well as the need to preserve existing structures, have sparked increased interest in assessment methods among scientists and professionals. These methods allow for safer, more cost-effective, and suitable corrective remedies [102-104]. Table 2 summarizes numerous commonly used NDT techniques for RCC structures, including their significant advantages, limits, parameter measurements, and primary applications. The approaches covered in this review are broadly classified according to the technology they use: mechanical, electromagnetic, ultrasonic, optical, radiographic, electrical, vibration-based, and strain-sensing methods.

4.1. How to Choose Appropriate NDT Methods

Choosing the appropriate Non-Destructive Testing (NDT) methods for concrete assessment involves a full understanding of a variety of factors in order to produce accurate and reliable results. The crucial consideration is the assessment's purpose. For example, if you want to evaluate the overall structural integrity of a concrete structure, you will need methods that can penetrate deeply and provide detailed information about the concrete's internal condition. This includes identifying inner flaws, voids, and cracks that could compromise the structure's safety.

The type of concrete under examination is also an essential consideration. New concrete may have different properties than older, potentially decaying, and concrete. Older concrete may require specialized procedures to investigate issues such as moisture content, which can affect its durability and strength over time. Environmental variables are also an essential consideration. Testing in controlled environments lowers the impact of external variables like as temperature and humidity, which may affect the accuracy of the results. However, in the field, methods must be adaptable to changing environmental conditions while still producing reliable data.

Accessibility to the testing area is also vital. Some testing processes are more effective in large, open areas, while others are better suited to confined spaces or complex geometries. The type of defect you are looking for will also influence your strategy selection. Surface defects necessitate different processes than subsurface defects, and the technique utilized must be sensitive enough to detect the specific type of defect present.

Budget and time limits are practical considerations that should not be overlooked. Some testing methods are less expensive and faster to complete, making them suitable for projects with limited resources or short deadlines. However, it is vital to establish a balance between cost and time efficiency, as well as the need for exact and reliable results. You can select the appropriate NDT method by carefully considering the following factors: the purpose of the assessment, the type of concrete, environmental conditions, accessibility, and the type of fault, budget, and time constraints. This ensures that the assessment is accurate and timely, leading in better decision-making and safer, more reliable concrete structures.

Table 1. *Different codes describing NDT methods.*

NO.	NDT METHOD	INTERNATIONAL STANDARDS AND CODE
1.	Schmidt Rebound Hammer test	ASTM C805/C805M; BS EN 13791:2019; BS 1881-202: 1986; ASTM D5873-14

NO.	NDT METHOD	INTERNATIONAL STANDARDS AND CODE
2.	Penetration Resistance	ASTM C 803-82/C803M; BS 1881 - 207
3.	Pull-Off testing	ASTM C1583/C1583M; BS EN 1542
5.	Ground Penetrating Radar (GPR)	ASTM D6087-08; ASTM D6432-11; BS EN 302 066 V2.2.1
6.	Half-Cell Potential	ASTM C876-91; BS 1881-201
7.	Radiographic Testing	BS 1881-205; ASTM E1742/E1742M-18; BS 4408-3; ASTM E94/E94M-17; ISO 19232-1:2013
8.	Ultrasonic Pulse Velocity (UPV)	ASTM C597-97; BS 1881-203: 1986; BS 4408-5:1974; BS EN 12504-4: 2021; ISO/DIS 8047
9.	Acoustic Emission	ASTM E2983-14:2019; ASTM E3100-17 ISO 16836:2019
10.	Impact –echo test	ASTM C1383-23; ACI 228.2R
11.	Laser Scanning	ASTM E3022; ISO 16331-1; BS 1192-4
12.	Infrared Thermography	ASTM D4788-88; ASTM C1060-11a ISO 6781-1:2023
13.	Visual Inspection	ASTM C823/C823M-12:2017; ACI PRC-201.1-08
14.	Electrical Resistivity	ASTM C1760-12; UNE 83988-1 & 2
15.	Vibration-based methods	ASTM C215-19; BS 1881-209:1990
16	Computer tomography	ASTM E1441; ISO 15708-1, 2 &3

Table 2. *Different NDT methods and parameter measured.*

No	NDT Methods	Parameter	Application	Limitation
1.	Schmidt Rebound Hammer test [7, 9, 33, 34, 38-41]	Surface hardness Compressive strength Uniformity of concrete	To estimate strength and assess uniformity of concrete to assure quality To estimate early edge strength rate of strength gain for construction scheduling	Surface condition affect results significantly Measures limited depth (20-30 mm) Not suitable for concrete strength beyond 60 MPa and lightweight concrete with density less than 1440 kg/m3 Difficulty to assess internal flaws
2.	Penetration Resistance (Windsor Probe) [42, 43]	Compressive strength Surface hardness Material uniformity	To estimate strength in place to ensure safety and durability of concrete The test was also applicable to evaluate lightweight concrete strength	The concrete thickness should be three times depth of probe penetration The test location must be away from Edge and rebar proximity Not suitable for concrete strength beyond 40 MPa Minimal hole left in concrete surface Difficulty to assess internal flaws
3.	Pull-Off testing [44-48]	Bond strength	To assess the adhesion strength of coating applied to flooring system and exterior coating and cladding systems to building facades Verifying the adhesion of waterproofing membranes and protective coatings on steel structures.	Affected greatly by surface preparation (surface cleanness, free of dirty and roughness) The test is partially destructive Temperature and humidity affect results moderately Require operator skills

No	NDT Methods	Parameter	Application	Limitation
4.	Ground Penetrating Radar (GPR) [10, 49-52]	Thickness measurement Void and crack detection Depth and position of rebar	Determine rebar formation and corrosion mapping within concrete structures Describing the thickness of concrete slabs and walls to ensure design specification Detect concrete deterioration and delamination	Resolution trade-off at dense materials making difficult to detect internals In heavily RC closely spaced bar (less than 7 cm) create signal clutter highly Surface condition (uneven or coating) can affect results Moisture content in concrete can affect accuracy of GPR
5.	Half-cell potential [35, 36, 53-56]	Corrosion potential Probability of corrosion Corrosion mapping	For assessment of the durability of reinforced concrete members where reinforcement corrosion is suspected.	Requires direct access to the concrete surfaces, which can be challenging in certain structures. Moisture content, temperatures and too thickness of concrete cover affect results Surface coating or overlays affect result greatly Provides a probability of corrosion rather than definitive measure Result interpreting requires experience and understanding of specific condition.
6.	Radiographic Testing [57-61]	Internal defects Thickness variation Density difference Reinforcement detail Structural integrity	To estimate bar size and location within concrete Detect concrete deterioration and delamination To control quality of materials and component meets specified standards	The ability of portable X-ray units penetration depth is limited up to 20 cm Requires strict safety measures Expensive and slower compared The setup and execution of radiography testing are complex The cost are relatively high
7.	Ultrasonic Pulse Velocity (UPV) [31, 32, 62-66]	Uniformity and density Compressive strength Depth of surface-breaking cracks	Evaluate quality and uniformity Detect internal flaws To predict concrete strength Detection of damage in concrete and to monitor structural health	Surface condition affect results significantly Moisture condition affect greatly For accuracy access to both sides of structures is often required Difficult to detect fine cracks Material heterogeneity can cause fluctuations in consistent reading They are less effective detecting defects beyond 50 cm in concrete
8.	Acoustic Emission [70-78]	Nature and Level of damage Damage mechanism Location of damage	To detect and locate damage Corrosion monitoring in RC To control quality of concrete Continuously to monitor structures	It requires good surface access to place sensor (rough surface hinder success) Environmental interference reduce reliability of test by up to 20-30% AE testing is more effective at detecting active defects that are growing Limited to detection range from sensor
9.	Impact–echo test [11, 37, 67-69]	Thickness Internal defects Characteristic of defect Mechanical properties	To assess delamination and voids To measure thickness and depth To detect and assessing the depth and extent of cracks To assess mechanical properties of concrete	Effective for limited depth (1 m) in concrete Surface condition can lead to poor signal Material heterogeneity within the concrete structure can scatter waves Environmental noise and operational vibration can interface IE signals
10.	Laser Scanning [79-81]	Volume and area Alignment and toler-	Dimensional analysis and tolerance checking	Requires clear access to the surface being scanned

No	NDT Methods	Parameter	Application	Limitation
		ance Floor flatness and levelness Deformation and deflection	Monitoring deformation and displacement To verify construction work	Reflective and transparent surfaces can distort the laser signals greatly Environmental condition reducing the accuracy and reliability High quality laser scanning equipment are expensive
11.	Infrared Thermography [12, 84-89]	Surface temperature Moisture content Insulation quality Energy efficiency	To detect delamination and voids To detect moisture intrusion in structures evaluating the effectiveness of insulation by identifying areas of heat loss	Limited to detect near-surface Environmental sensitivity for ambient temperature, wind and sunlight Surface condition affects greatly the accuracy of readings Not effective for concrete due to low thermal conductivity Requires experienced experts
12.	Visual Inspection [82, 83]	Surface condition Discoloration, efflorescence, spalling and staining Corrosion of reinforcement Joint condition Structural deformation	To gain information in construction methods and faults, weathering, chemical attack, visible mechanical damage and physical deterioration To evaluate overall structural condition To conduct routine safety inspection	Surface-only detection difficult to detect internal flaws Highly subjective and human factor Does not provides quantitative data's about material properties like strength Very small defects may not be noticed Poor lighting, weather condition and accessibility can affect accuracy
13.	Electrical Resistivity [90-96]	Pore structures Moisture content Chloride ion penetration Permeability	To assess durability BY measuring chloride ion penetration To measure the potential for corrosion in steels within concretes To measure the moisture content in concrete	Influenced by moisture content and temperatures in structures Affected results up to 30-40% by presence of aggregate and steel Surface condition can lead to errors by up to 20-30% It provides an resistivity values over the areas it can mask localized defects within the concrete
14.	Vibration-based methods [97]	Natural frequencies Mode shapes Damping ratio Modal strain energy	To detect damage and dynamic property for structural health monitoring To assess the seismic performance of structure	Environmental sensitivity (traffic, wind and machinery) affected significantly Not more effective in detecting localized damage Requires accurate baseline measurements of the structures vibration characteristics Temperature affects slightly results
15.	Strain sensing methods [98]	Axial and shear strain Crack width Temperature Pre-stressing force	To detect early structural issues (cracks or deformation) To evaluate the performance and load bearing capacity of structures To monitor fatigue and seismic in structures	Temperature variation affects reading by up to 10-15% High quality strains sensors significantly more expensive Over time sensor degradation lead to gradual decrease in accuracy Installation challenge lead to errors as much as 5-15%

4.2. Comparison of NDT

In the construction industry, material integrity and dependability are crucial. Non-Destructive Testing (NDT) protocols are essential for assessing various parameters without inflicting damage. We evaluate NDT methods based on their capacity to determine compressive strength, internal fault identification, reinforcing features, complexity, and other factors. Table 3 outlines the efficacy of non-destructive testing (NDT) approaches in concrete condition evaluation.

Table 3. Comparison of NDT methods for concrete condition assessment.

No.	Non-Destructive Testing Methods (NDT)	Effectiveness Of NDT In Concrete Condition Assessment FOR:			
		Comp. Strength	Internal flaws detect	Rebar details	Others parameter good
1.	Schmidt Rebound Hammer test	Good	Limited	Not-valid	
2.	Windsor Probe	Good	Limited	Not-valid	
3.	Ground Penetrating Radar (GPR)	Not-valid	Good	Excellent	
4.	Radiographic Testing	Not-valid	Excellent	Limited	
5.	Ultrasonic Pulse Velocity (UPV)	Excellent	Excellent	Limited	
6.	Acoustic Emission	Not-valid	Excellent	Not-valid	
7.	Laser scanning	Not-valid	Not-valid	Not-valid	Dimention analysis
8.	Pull-off testing	Not-valid	Not-valid	Not-valid	Adhetion strength
9.	Impact-echo method	Not-valid	Excellent	Limited	Thickness measurment
10.	Infrared Testing	Not-valid	Good	Limited	Thermal property
11.	Half-cell potential methods	Not-valid	Not-valid	Limited	Corosion detection
12.	Electrical resistivity method	Not-valid	Not-valid	Limited	Corosion & moisture content detection
13.	Vibration-based methods	Not-valid	Not-valid	Not-valid	Dynamic response
14.	Strain sensing methods	Not-valid	Not-valid	Not-valid	Deformation & stress

: Excellent : Good : Limited : Not-valid

Comparison Between Different Works

Several research projects have been undertaken to evaluate the condition of concrete using various NDT methods in order to establish a correlation between the methods and concrete property parameters. In this section, we explain how different research have graphically connected UPV and SRH methodologies with concrete compressive strength, as seen in Figure 1a and 1b. The goal is to acquire a general overview and emphasize what appear to be common rules. In truth, seeming discrepancies are common: many distinct types of empirical correlation are utilized, and the coefficient values for each type can vary across a wide range. This variation could be caused by a variety of factors, including aggregate proportions, water/cement ratio, and curing, but it does not imply a lack of confidence in this procedure.

Several reasons can explain the differences in correlation between ultrasonic pulse velocity (UPV) and Schmidt rebound hammer test and compressive strength recorded by different researchers. These include variations in concrete mix designs, such as water-cement ratios and aggregate kinds, which influence both UPV and rebound hammer readings. The rebound hammer test findings can be influenced by the quality of the concrete surface, including moisture content and smoothness, whereas interior faults and uniformity have an impact on UPV values. Variations in testing processes, such as the rebound hammer's angle of impact and ultrasonic equipment calibration, all lead to variances. Temperature and humidity might also have an impact on testing outcomes. Furthermore, the statistical methods utilized to evaluate data and derive correlations can vary between investigations.

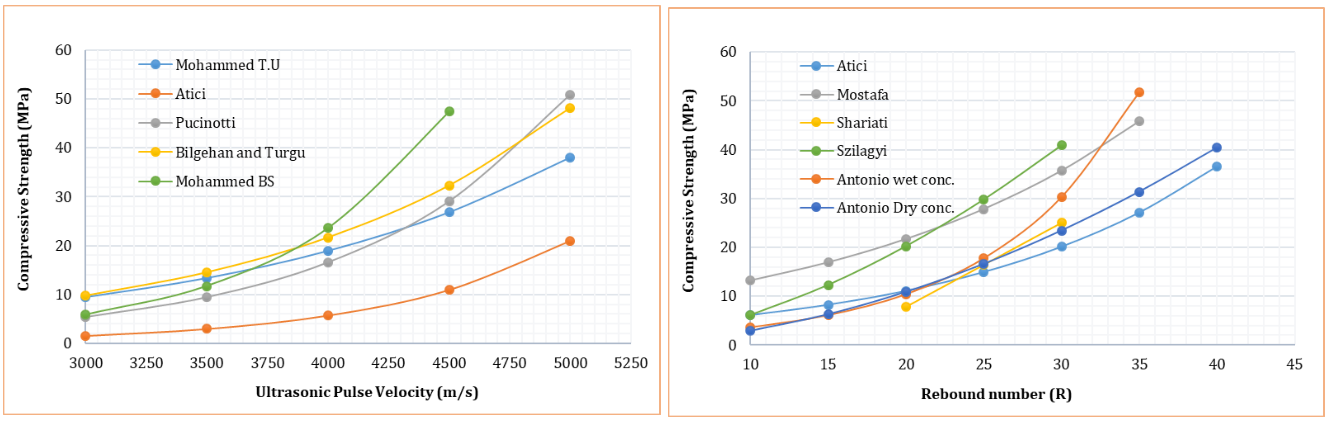

Figure 1. *Illustration of the variety of studies (original sources for models provided in references [1-9]).*

To increase the consistency and reliability of correlations between UPV, Schmidt rebound hammer test, and compressive strength, concrete mix designs should be standardized to ensure constant w/c ratio and aggregate types throughout investigations. The rebound hammer test requires equal surface conditions, such as moisture content and smoothness, whereas UPV measurements require homogeneity and the absence of internal flaws. Standardized testing processes, such as uniform rebound hammer impact angles and correct ultrasonic equipment calibration, can help to reduce variability. Controlling environmental parameters like as temperature and humidity during testing is also critical. Using strong statistical approaches for data analysis and conducting interlaboratory studies to validate findings can help to improve the dependability of the relationships.

4.3. NDT Result Interpretation

Non-Destructive Testing (NDT) procedures are crucial instruments for evaluating and maintaining concrete buildings. These procedures enable for the examination of concrete's integrity, strength, and durability without causing structural damage. The fundamental goal of NDT is to give accurate data that can be utilized to make informed judgments concerning the safety and condition of concrete buildings. Interpreting the findings of these procedures is a vital stage in this process. It necessitates a thorough understanding of the principles underlying each method, as well as the capacity to correlate the data with the actual state of the concrete. It entails assessing data collected from various testing methodologies in order to evaluate the physical and mechanical properties of concrete. This study aids in identifying potential problems like as fractures, voids, and other flaws that may jeopardize structural integrity.

The results of NDT procedures correlate with numerous tangible qualities, providing information about the material's state and performance. However, interpreting NDT data for concrete can be difficult due to its heterogeneous nature, variations in aggregate size, type, and distribution, and curing conditions. Surface characteristics, such as roughness and moisture content, might have an impact on the efficiency of certain NDT procedures. Understanding these correlations and obstacles allows engineers and technicians to better interpret NDT results, resulting in more accurate assessments of concrete structures. Future advances are likely to improve the accuracy, efficiency, and applicability of NDT technologies, making them even more effective tools for structural evaluation. Table 4 shows how the NDT results are interpreted.

Table 4. *Interpretation of NDT results for concrete assessment.*

	NDT Method	Results	Interpreting NDT output
1.	Schmidt Rebound Hammer test	Rebound number	Each hammer comes with a coversion chart that translate rebound nuber into estimated compressive strength.
2.	Ground Penetrating Radar	Radargram	The radagram displays the refelected signals. The key aspect to interpre include: 1) Hyperbola: indicate the presence of discrtet objects like rebar or voids. 2) Continous Line: shows layer interferance or chnage in material properties 3) Signal Amplitude: strong reflected signal indicates density and uniformity
3.	Radiographic Testing	Radiographic Image	The radiographic image are examined and the key aspect to interpre include: 1) Dark areas: Indicate less dense regions, the presence of internal flaws

	NDT Method	Results	Interpreting NDT output
			2) Light areas: Suggest sound materials absorb more radiation 3) Sharp edge: specify the presence of cracks or sharp discontinuities 4) Blurry areas: Suggest gradual change in material density, such as porosity
4.	Ultrasonic Pulse Velocity	Velocity	The primary output is pulse velocity, calculated using $V = L/T$; (L is distance between transducers; T is time travel of ultrasonic pulse). The values interpreted as: below 3 km/s (Doubtful quality); 3.0 to 3.5 km/s (Medium quality); 3.5 to 4.5 km/s (Good quality); above 4.5 km/s (Excellent quality). The empirical relationship is established between pulse velocity and compressive strength of concrete using regression analysis.
5.	Impact-echo method	Time-domain waveform	Graphs showing the arrivals time and amplitude of the ultrasonic waves. The amplitude of the wave provide about the materials properties. The raw data is transformed into frequency domain using Fast Fourier transform (FFT). The primary peak in the frequency spectrum corresponds to the thickness of concrete or flaws depth. Higher frequency indicate shallower defects while low frequency indicate deeper defects.
6.	Infrared Testing	Thermal image	Thermal images displays tempreture variations using color maps. Different colors represents different tempreture, Blue and purple (Cool ares indicate sound materials or areas without defects, Green (Room tempreture indicate normal condition without significat defects), Yellow and orange (Warm areas suggest voids, delamination or moisture), Red: (higher tempreture suggest significant defects) and White (hottest area suggest sever defects)
7.	Electrical resistivity method	Resistivity value	High resistivity >20 kΩ-cm: [Indicates low permeability and high durability] Moderate Resistivity 10-20 kΩ-cm: [Indicates moderate permeability and durability] Low resistivity <10 kΩ-cm: [Indicates high permeability and low durability]

5. Case Studies

5.1. Laboratory-Designed Experiment Using Infrared Thermography (IF) for Concrete Pavement Condition Assessment

Introduction: Yang Lu et al. [12] carried out a laboratory-designed experiment with IR methods. Thermal transfer modeling was also employed to help with IR imaging test setup. In their experiment, they used active thermography in the form of a certain temperature threshold to process their photos and obtain a digital indication of where the flaws were located. In this temperature range, the quantity of thermal energy distributed on the specimen's surface is calculated and extracted from the thermal image using image-processing techniques.

Methodology: In this investigation, picture data was captured using a FLIR thermal camera (model T430sc). The object distance is set from 0 to 1 meter, and the air temperature is set at 20 ℃ (similar to lab temperature). They employed a simple approach to create lab-scale concrete specimens. To simulate genuine pavement subsurface faults, many alternative shapes of delamination in different depths of the specimen are used to determine which depth is most appropriate and provides the best contrast in thermal pictures. Each cylinder has a diameter of 4" and a height of 8". A 3 cm Styrofoam cube was utilized as a delamination, positioned 5 and 10 millimeters beneath the surface. A hot air blower with a temperature of up to 63.5 ℃ heats the surface for 20 minutes. The thermal image was captured three minutes into the specimen's cooling cycle (while maintaining the bottom side of the concrete submerged in ice water).

Results: According to the writer, the surface on top of the delamination has a higher temperature than the sound region (concrete), which has a low heat conductivity; hence, the temperature differential allows them to estimate where the faults are inserted. A temperature versus distance graph is created using the pixel data from line 1 (as shown in Figure 2), which is located in the center of the specimen's surface. A clear correlation has been discovered between the temperature gradient and the depths of flaws beneath the surface. The writer observes a temperature difference of 2 ℃ between defects 1 (61.5 ℃) and 2 (63.5 ℃).

The researcher justified shallower delamination with a higher temperature region on the surface, which will be closer to the actual area of the delamination's surface when processed. Using POA, we can create a system that allows us to determine the area of an unknown delamination based on its depth beneath the surface of the concrete specimen. Table 5 compares the delaminated areas exhibited in the processed thermal picture to the actual area of the surface of the faults introduced into the concrete specimen.

Table 5. *Area of processed image comparison.*

	AREA OF DEFECTS	NUMBER OF PIXELS	IR MEASUREMENT OF AREA	PERCENTAGE OF ACCURACY
1.	Actual Area Of Defects	30276	9 cm^2	100%
2.	The 5 mm Deep Defect	21286	6.33 cm^2	$\frac{6.33}{9} \times 100 = 70.33\%$
3.	The 10 mm Deep Defect	5727	1.7 cm^2	$\frac{1.7}{9} \times 100 = 18.88\%$

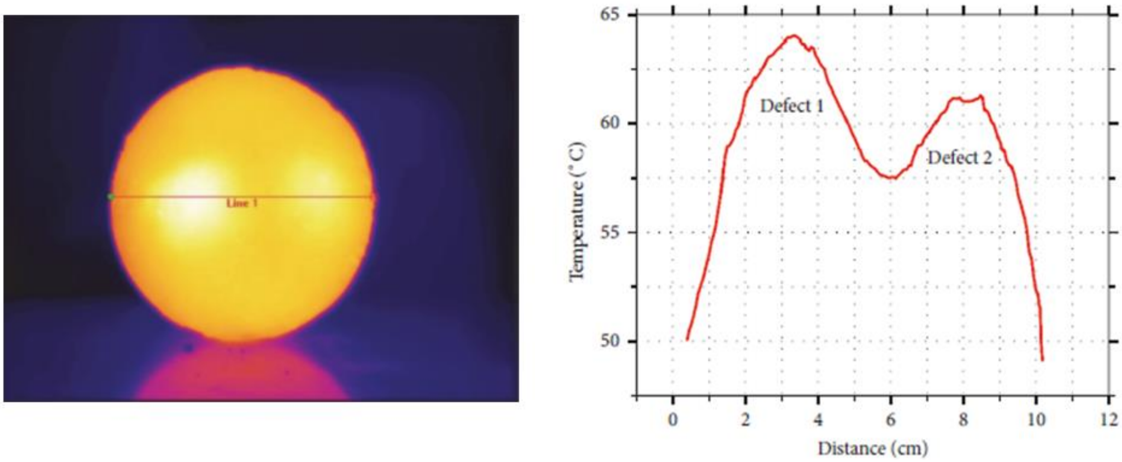

Figure 2. *Temperature versus distance graph assigned to line 1 in surface of the specimen (original sources for models provided in [12]).*

Conclusion: With a set of precise material properties, we can forecast the experimental tests in a controlled laboratory setting. The proposed IRT method has been validated as an effective alternative to inspecting concrete pavements.

5.2. Application of Impact-Echo Method for Mechanical Properties Assessment of Post-Fired Concrete

Introduction: assessing the mechanical properties of concrete after exposure to fire is critical for assuring structural safety. Katarzyna Krzemien and Izabela Hager [11] designed a laboratory experiment at Cracow University of Technology to perform a resonance frequency test on concrete and determine a relationship between the characteristics measured using the impact-echo device (i.e. the nature of the signal in the frequency domain) and the residual properties of concrete determined by mechanical tests after exposure to high temperatures.

Methodology: Tests were conducted on concrete cubes with sides measuring 0.15 m in length to determine the relationships between the parameters measured with the impact-echo device and the mechanical properties of specimens obtained using standard destructive methods. Cubic specimens were heated in a laboratory furnace at 0.5 ℃ per minute. After reaching the desired temperature (T = 200 ℃, 400 ℃, 600 ℃, 800 ℃, 1000 ℃), the cubes were kept at that temperature for three hours to ensure uniform temperature dispersion. The specimens were then cooled in the oven at an unregulated rate. After the specimens had cooled down, impact-echo and destructive tests were performed to evaluate the relationships between the measured data.

Results: The captured data represented the amplitude of surface vibration over time. The signal received in the time domain was converted to the frequency domain using the Fast Fourier Transform (FFT), allowing the determination of a resonant frequency f. Once the resonant frequencies f for a certain temperature and thickness of tested object are known, the velocity of propagation of an elastic wave produced on the specimen surface can be calculated using the formula (1). Having determined the propagation velocity, the dynamic modulus of elasticity (Ed) might be calculated using the formula (2).

$$Vp = {}^{2Tf}/_{\beta} \tag{1}$$

$$Vp = \sqrt{\frac{Ed(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{2}$$

Where Vp is the velocity of elastic wave propagation, ρ is the density of the material, v is the Poisson's ratio, Ed is the dynamic modulus of elasticity, β is the thickness-to-width ratio, and T is the sample thickness (0.15 m).

All of the observations discussed above are shown in Figures 4 and 5. According to the authors, the post-fire assessment of mechanical characteristics of concrete using the impact echo device, the resonant frequency (f) and velocity of signal propagation (Vp) were integrated with the compressive strength of concrete (fc). The type of the signal captured in time domain had a very strong relationship with the extent of heat damage in concrete (as illustrated in Figure 3).

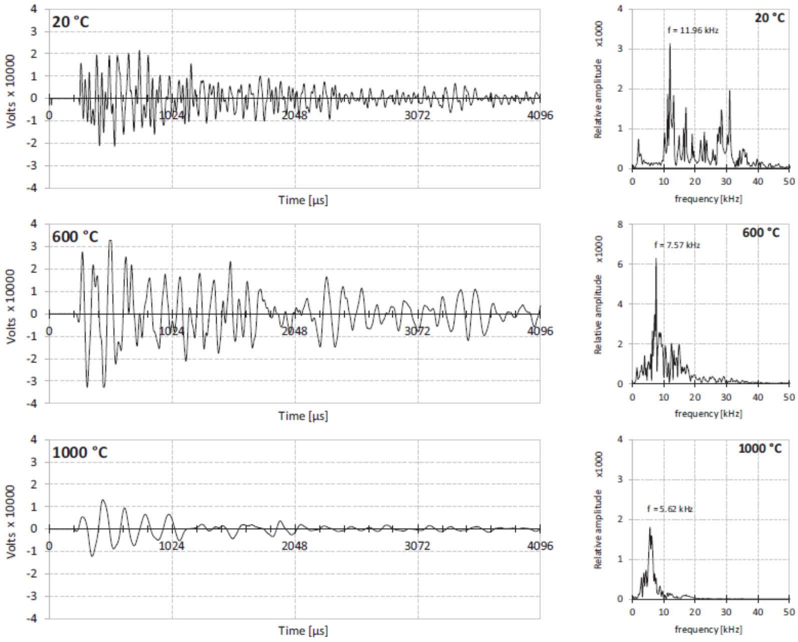

Figure 3. *Example of signals recorded in time domain for temperature of 20 ℃, 600 ℃ and 1000 ℃; the signal transformed to the frequency domain by FFT (original sources for models provided in [11]).*

Conclusion: The authors concluded their research by claiming that the impact-echo method is a good non-destructive tool for testing the quality and mechanical properties of concrete exposed to fire. The lengthening of the oscillation period in the time domain signal, which is associated with greater thermal degradation, leads in lower maximum resonant frequencies. This method's examination of resonance frequency is very useful for evaluating compressive strength. Furthermore, the agreement of impact-echo parameters with mechanical qualities such as residual compressive strength and static modulus of elasticity demonstrates their reliability. Therefore, the impact-echo method is effective for post-fire evaluation of concrete.

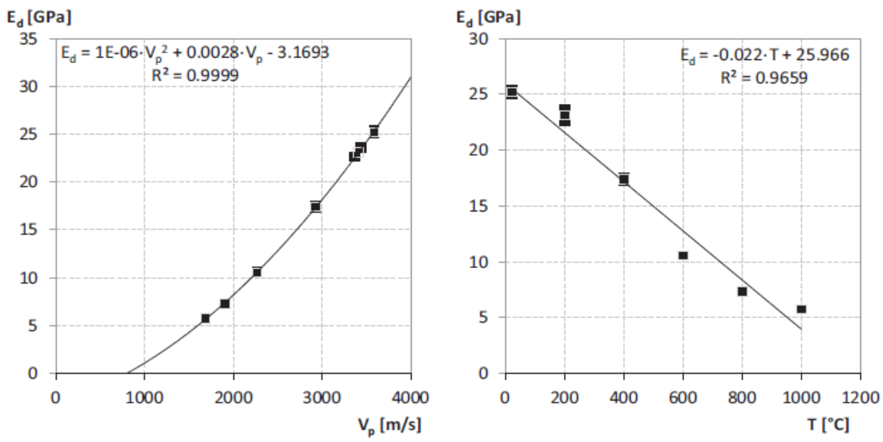

Figure 4. *Relation between dynamic modulus of elasticity (E_d) and velocity of signal propagation (Vp) (original sources for models provided in [11]).*

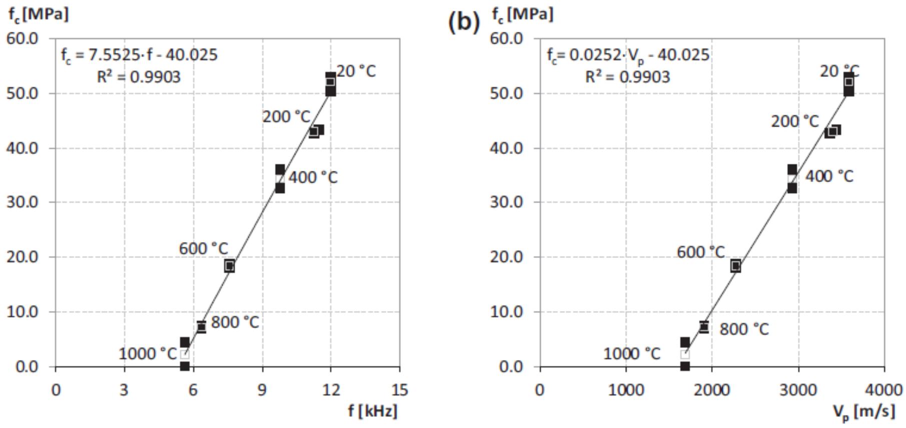

Figure 5. The relationship between compressive strength of concrete subjected to high temperature (fc) with resonant frequency of elastic wave (f) and velocity of wave propagation (Vp) (original sources for models provided in [11]).

5.3. Applications of Ground Penetrating Radar (GPR) in Bridge Deck Assessment

Introduction: This case study investigates the use of ground penetrating radar (GPR) in the assessment of the Forth Road Bridge, a suspension bridge, using the experience of the University of Greenwich Department of Civil Engineering and Bridge and Tunnel Engineering by Alani and Aboutalebi [10]. The Forth Road Bridge is located in eastern central Scotland. The study focuses on a comprehensive inspection of the bridge, with a special emphasis on identifying potential faults such as structural cracks within the deck structure and determining the arrangement of the upper and lower rebar placements across the bridge.

Methodology: The GPR survey was carried out utilizing the RIS HI-BrigHT Bridge High Resolution Tomography. Specifically designed for inspection of bridge decking. It was specifically developed to work in tandem with modern software processing, enabling for the detection of shallow features and the structure's state. The survey was carried out by pushing the device in an 80 cm grid, with 10 cm interval between scans. For best results, the radar was pushed in both transverse and longitudinal directions. These scans can be evaluated to produce photographs and recover information about the state of the building's constituent materials.

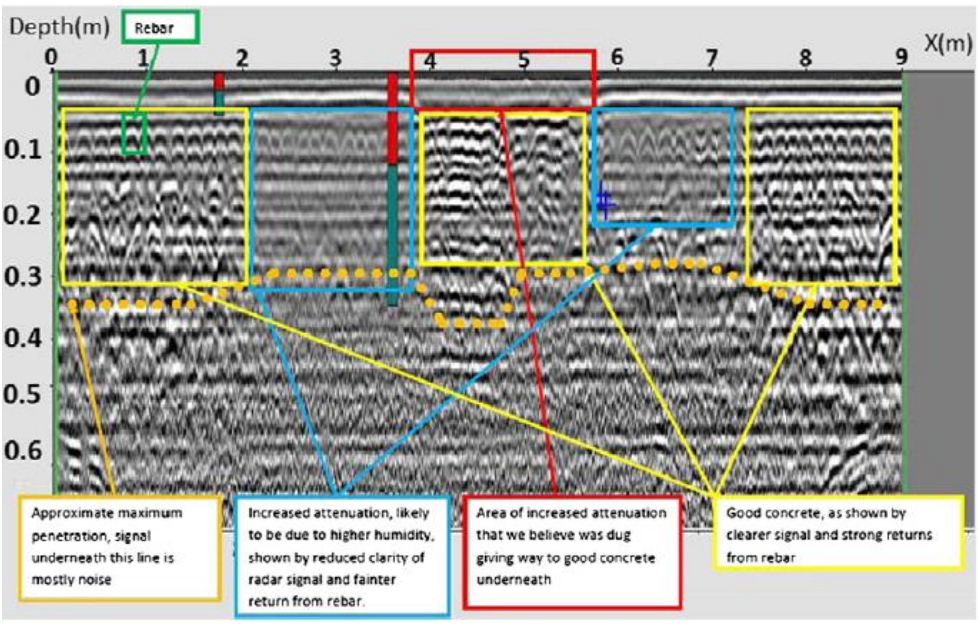

Figure 6. Longitudinal scan depiction of a section of the bridge with identified feature (original source for survey provided in [10]).

Results: Figure 6 depicts a longitudinal scan with annotations to identify features observed during the radar survey. This interpretation can be used to multiple scans side by side to create a picture of the conditions inside the bridge. According to their Alani et al. [10], the findings gave useful information about the structural integrity of concrete. The tests demonstrated that the maximum penetration depth into concrete was roughly 0.3-0.4 meter; this depth aided in the detection of humidity within the concrete, as evidenced by diminished radar signal quality and fainter rebar reflections. Furthermore, zones of attenuation were observed, which normally indicate high-quality concrete due to its homogeneous density and low moisture content.

Conclusion: The case study by Alani et al. [10] demonstrates that the offered results are credible in terms of achieving the investigation's objectives. It was feasible to achieve the necessary answers to a number of difficult questions and more through attentive and careful planning, survey (referencing), data collecting, data processing, and interpretation. Without a doubt, GPR is useful and decisive when utilized properly and appropriately.

5.4. On Site Assessing the Strength of Reinforced Concrete Structures Using SonReb Method

Introduction: Evaluating reinforced concrete structures is critical for assuring their safety and durability. Non-destructive testing procedures, such as ultrasonic pulse velocity and Schmidt Rebound Hammer tests, have shown to be excellent tools for determining concrete strength and integrity. Shariati et al. [7], from the University of Malaya's civil engineering department conducted detailed on-site assessments to determine the concrete's in-situ compressive strength. The goal is to establish a correlation between the independent variables (rebound number, ultrasonic pulse velocity) and the dependent variable (compressive concrete strength) in order to assess the strength of standard laboratory samples and core samples taken from existing buildings.

Methodology: According to Shariati et al. [7], the pulse velocity measurements utilized for columns are direct, semi-direct for beams, and in-direct for slabs. The latter method is appropriate for assessing concrete quality, whereas solely the modulus of elasticity rather than the shape of the concrete determine pulse velocity. Non-destructive approaches for determining the actual compressive strength of concrete in existing structures rely on experimental relationships between strength and nondestructive factors. The regression analysis approach is employed as destructive testing in this study to obtain a mathematical link between SRH and UPV for investigating reinforced concrete buildings.

The rebound number was calculated by obtaining 36 readings for the column, 18 for the beam, and 24 for the slab. Readings were taken horizontally for beams and columns and vertically for slabs. The mean rebound number and mean strength acquired from specimen compression strength tests gave the data needed to design a correlation curve. The UPV values include 36 readings for the beam, 12 for the column, and 20 for the slab. For this test, the mean strength received from UPV and the mean strength collected from each member provided the data required to create a correlation curve.

Results: Table 6 highlights the association between expected and compression strength of concrete, which is obtained through regression analysis of average rebound number/ultrasonic pulse velocity against compressive strength of each member. The author justified the Schmidt Hammer Rebound (SRH) using the best-fit line, which has a higher correlation than UPV. The regression model obtained with SonReb approaches is more exact and closer to the experimental results than the results obtained using individual methods.

Conclusion: The rebound number method appears to be more accurate in forecasting concrete compression strength than the ultrasonic pulse velocity method. However, the construction of calibration curves to conform to the Schmidt Rebound Hammer (SRH) and the UPV testing methodologies for typical concrete mixes demonstrated that using these two methods alone is insufficient to forecast an accurate estimate of concrete strength. The Schmidt Rebound Hammer (SRH) test is not advised for estimating the strength of in situ concrete without the use of a specialized calibration chart.

When compared to using the following approaches individually, using combined methods yields more reliable findings that are closer to true values. An adequate level of precision was also noted for concrete strength estimation. As a result, for engineering investigations, the derived regression model for strength evaluation could be employed safely to estimate concrete strength.

Table 6. *Schmidt rebound hammer, Ultrasonic pulse velocity and SonReb method correlation with compressive strength [7].*

	Results	Correlation	No. of used data (n)	R^2	Standard Error
1.	Schmidt Rebound Hammer (SRH)	$fc(R) = 1.7206R - 26.595$; R is the rebound number	18	93.6%	2.1024
2.	Ultrasonic Pulse Velocity (UPV)	$fc(V) = 15.533V - 34.358$; V is ultrasonic pulse velocity.	18	91.9%	3.3746
3.	SonReb	$fc(V) = -173.04 + 4.07V^2 + 57.96V + 1.31R$	18	95%	1.8491

6. Discussion

Non-destructive testing (NDT) procedures for examining concrete structures have advanced significantly in recent decades. These technologies offer significant insights into the integrity and durability of structures while inflicting no damage, making them indispensable tools in modern engineering and conservation procedures.

The procedures use a number of technologies to assess the state of structures. They provide real-time data on interior faults, voids, and other irregularities that are not visible with the human eye. This skill is especially useful for maintaining and protecting ancient structures, since typical invasive treatments may cause irreversible harm. The ability to conduct extensive assessments without jeopardizing structural integrity is a key advantage since it ensures that both new and existing damaged structures can be saved and maintained successfully.

Despite their various benefits, NDT techniques have limitations. These methods' accuracy can be modified by a variety of factors, including material qualities, environmental circumstances, and the operator's skill level. Certain climatic circumstances, for example, can alter the readings of particular NDT methods, whilst the variability of building materials complicates result interpretation. Furthermore, the initial cost of NDT equipment and the requirement for specialized training can be prohibitively expensive for some firms. These issues need careful method selection and an understanding of their limitations.

In practice, NDT techniques have been effectively used in a variety of situations to ensure the safety and longevity of concrete. For example, they have helped assess the state of bridge decks, locate delamination zones, and detect moisture intrusion and temperature anomalies in building envelopes. These real-world examples demonstrate the practical benefits of NDT technologies by providing detailed assessments that inform maintenance and repair solutions.

7. Potential Direction

The integration of sophisticated technologies like artificial intelligence (AI) and machine learning (ML) is predicted to transform NDT [105, 106]. AI and ML systems can analyze massive volumes of data generated by NDT procedures, revealing patterns and anomalies that would otherwise go undetected. This can result in more accurate fault detection and predictive maintenance models, ultimately increasing the dependability of structural assessments. Advances in data visualization and interpretation tools will help engineers understand and act on the results of NDT examinations. Enhanced imaging technologies, such as 3D and 4D visualization, will provide more detailed and intuitive depictions of structural conditions [107].

The integration of NDT data with Building Information Modeling (BIM) systems represents a promising future direction [108, 109]. BIM creates a digital representation of a building's physical and functional properties, and adding NDT data into these models can provide a complete picture of the structure's condition. This integration can help with maintenance planning, asset management, and lifetime analysis, resulting in more efficient and effective building management.

The use of remote and automated NDT systems will improve the safety and efficiency of structural examinations [30, 110, 111]. Drones and robotic systems equipped with NDT sensors can enter difficult-to-reach regions and conduct inspections without endangering human operators. These systems can perform continuous monitoring, delivering real-time data on structure health and allowing for timely intervention when problems are recognized.

Drones and robotic systems equipped with NDT sensors can enter difficult-to-reach regions and conduct inspections without endangering human operators. These systems can perform continuous monitoring, delivering real-time data on structure health and allowing for timely intervention when problems are recognized.

8. Recommendations

1) Combine a multi-method approach for comprehensive assessment that can provide a more complete picture of the concrete condition.
2) Establish comprehensive training programs in NDT to ensure that technicians are well-equipped to perform high-quality NDT assessments and interpret results.
3) Encouraging research and development in NDT can drive innovation and improve existing techniques to foster the development of new technologies and methods.

9. Conclusion

The use of non-destructive testing (NDT) techniques in the evaluation of concrete structures has proven to be a game changer in structural engineering. The important findings of this review can be stated as follows:

1) The reviews found a variety of NDT methods for assessing different concrete qualities, each with its own set of advantages and drawbacks. The methodologies used are determined by the assessment's unique criteria as well as the state of the concrete structures.
2) Adherence to established standards and guidelines, such as ASTM and BS, is critical for ensuring consistency and quality in NDT results for concrete assessment, as it provides a framework for conducting tests and interpreting results.
3) The selection of appropriate NDT methods includes examining numerous criteria, including the kind of con-

crete, the structure's state, and the assessment objectives.

4) A comparative review of various studies demonstrates that no single strategy is preferable globally. Instead, the efficiency of each method varies with the context and assessment criteria. Using various NDT methods frequently produces the most accurate results.
5) Interpreting NDT data necessitates a detailed understanding of the underlying principles of each approach and the variables that influence the measurements. As a result, in this review, some typical challenges in result interpretation and how to overcome them have been addressed.

As technology advances, these procedures will become increasingly precise and efficient; giving engineers powerful tools for structural assessment and decision-making. The continued development of NDT techniques will strengthen their position in structural engineering by assuring the safety, durability, and preservation of our built environment for future generations.

Abbreviations

ACI	American Concrete Institute
AI	Artificial Intelligence
ASTM	American Society for Testing and Materials
BIM	Building Information Modelling
BS	British Standard
EDS	Energy Dispersive Spectroscopy
FFT	Fast Fourier Transform
GFRP	Glass Fiber Reinforced Polymer
GPR	Ground-Penetrating Standard
ISO	International for Standardization
IRT	Infrared Thermography
ML	Machine Learning
NDT	Nondestructive Testing
QC	Quality Control
QA	Quality Assurance
RC	Reinforced Concrete
RCC	Reinforced Cement Concrete
SFRC	Steel Fiber Reinforced Concrete
SHM	Structural Health Monitoring
SRH	Schmidt Rebound Hammer
UAV	Unmanned Aerial Vehicle
UPV	Ultrasonic Pulse Velocity

Author Contributions

Belay Bayu Tefera: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Visualization, Writing–original draft

Abrham Gebre Tarekegn: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing–review & editing

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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