K. Schabowicz[1*], A. E. Menéndez Orellana[2], N. Andrianos[3]
1 Professor, Wrocław University of Science and Technology, Poland
2 Wrocław University of Science and Technology, Poland
3 Hellenic Mediterranean University, Heraklion, Greece

Analysis of selected non-destructive methods for diagnosis in new and old buildings

Analiza wybranych metod nieniszczących diagnostyki w nowych i starych budynkach

STRESZCZENIE

Techniki badań nieniszczących (NDT) są na dzień dzisiejszy podstawowym narzędziem stosowanym w inżynierii lądowej. Na podstawie szczegółowego przeglądu literatury przedstawiono w artykule kompleksową ocenę stanu technicznego budynku z zastosowaniem szeregu metod NDT. Ponadto przedstawiono odniesienia do publikacji zawierających opisy, zastosowania i studia przypadków każdej z metod NDT.

Słowa kluczowe: *konstrukcje betonowe; badania nieniszczące (NDT); konserwacja oparta na stanie (CBM); monitorowanie stanu strukturalnego (SHM).*

ABSTRACT

Non-destructive Testing (NDT) techniques are, as of today, a fundamental tool in civil engineering. Based on a thorough literature review, the scope of this article comprises a comprehensive assessment of the state-of-the-art of a series of NDT methods utilized specifically for concrete diagnosis, grouped into seven categories according to their main aim. Moreover, a summary of references to publications containing descriptions, applications, and case studies of each one is also presented.

Keywords: *concrete structures; non-destructive testing (NDT); condition-based maintenance (CBM); structural health monitoring (SHM).*

1. Non-destructive Testing (NDT) of concrete: Introduction

Reinforced concrete (RC) is one of the most widely used materials around the world. Even when understood to be a versatile and strong material which can endure significant external degradation, concrete experiences loss of integrity over time due to damage caused by chemical (alkali–silica reaction, carbonation, corrosion, crystallization, leaching, salt, and acid action…), physical (temperature variations, fatigue, overloading, shrinkage, freeze–thaw cycles...) and even biological (accumulation of organic matter, living organisms...) mechanisms. Understanding the multiple deterioration processes is crucial, as each process leads to different types of defects (corrosion of steel, cracking, spalling, delamination…) [1].

Around 3% of the world's gross domestic product (GDP), US$ 2.2 trillion, has been reported from world statistics as losses owing to premature deterioration of concrete [2]. Deterioration is, as a matter of fact, a major problem in any concrete element during its life cycle. That is where NDT methods prove indispensable.

While there is no standard definition for NDT of concrete specifically, the concept generally refers to methods that allow for objects, materials or systems to be examined without impairing their future serviceability; that is, to inspect or to measure without harm [3].

NDT methods are essential for regular monitoring, condition evaluation, quality assessment, and maintenance along different stages of the life of concrete structures. They have drastically reduced the time required to detect, analyze and diagnose structural problems. And besides facilitating condition-based maintenance (CBM), these methods have certainly opened the door to new possibilities for structural health monitoring (SHM).

The idea of this article is to serve as a guide on NDT of concrete structures, in a similar way as the Guidebook [4] published in 2002 by the International Atomic Energy Agency (IAEA) in Vienna was at that time, but with a contemporary approach aimed at updating the knowledge on concrete NDT through comments, findings, and references to conclusions from research studies and innovative works by authors around the world in recent years.

It cannot be overemphasized that, even if the main focus of this article are concrete structures, NDT not only belongs in concrete, let alone only in civil engineering. Its usefulness extends to a wide variety of industries and materials.

1.1 A brief history of NDT of concrete over time

An excellent reference on the matter can be found in the paper titled "Nondestructive Testing of Concrete: History and Challenges" by Carino (1994). From a historical perspective, the author commented on a series of milestones in the development of NDT methods. A timeline of the progress of NDT for hardened concrete along the 50 years previous to the publication of the paper in question is

*Autor korespondencyjny.
E-mail: krzysztof.schabowicz@pwr.edu.pl

Published by „Badania Nieniszczące i Diagnostyka" Publishing Agenda of SIMP
DOI: 10.26357/BNID.2022.008

described, toetheith an outline of future directions and challenges for the XXI century [5]. According to the author, the end of the XX century was an exciting time in terms of NDT of concrete, as new methods were on the horizon.

Carino emphasizes the contributions of V.M. Malhotra toward NDT development. It is worth recalling that in his 1977 landmark paper on the subject of testing cores versus in-place test methods, Malhotra made a call for a change to the status-quo for quality control of concrete. He argued that the current practice based on the standard-cured cylinder strength is ineffective, and concluded: "In order to create some semblance of order in an otherwise chaotic situation, a completely new approach has been suggested. This, of course, will involve fundamental changes in our approach to specifications and code writing, and could take some time before the concrete community accepts it" [5]. Carino quoted the latter in 1994, and in fact, Malhotra's suggestion remains now in 2022 -almost 50 years later- a goal yet to be achieved.

1.2 Classification of NDT methods

NDT methods are frequently classified by authors based on the nature of their governing principle. Nonetheless, it is also suitable, and very much helpful, to categorize these methods according to which parameters are meant to be evaluated by them. The reason why this last criteria is not so often used is likely because, in fact, the usefulness of the majority of NDT methods is not limited to a single aim.

Below, a series of contemporary NDT methods have been grouped into seven categories according to their most frequent application. Table 1 presents a summary of relevant literature for each one, in which a technical description of the methods can be found, as well as their applications, general advantages and disadvantages. Furthermore, there are also references to case studies that either illustrate the way in which the techniques prove useful for concrete diagnosis, or present findings of research work focused on their improvement.

Yet, it is important to emphasize that neither these groups, nor the listed methods, are intended to be exhaustive. Other authors present different categories which enclose additional NDT methods outside the scope of this article.

2. Fundamental challenges associated with NDT of concrete

Carino pointed out that, compared with the development of NDT methods of other materials like steel, NDT of concrete has run at a slower pace. The latter, due to the fact that concrete is an inherently more difficult material to test than steel, and the already developed technology cannot be directly transferred from one material to the other [5].

NDT challenges might, quite often, relate to the testing process itself. For instance, data collection for the Ultrasonic Echo method is usually labor-intensive and time-consuming. A careful calibration of the tomographer is required when starting a testing set, and due to its size, it is not easy to use within confined areas [20]. Another example is the IE technique, which is only effective for detecting certain

Tab. 1. Przykładowe energie uderzenia dla różnych obiektów upadających na strukturę [9].

Tab. 1. Exemplary impact energies for different objects falling on the structure [9]

Aim		NDT method	References
Evaluation of concrete quality	*Based on stress waves*	Ultrasonic pulse velocity (UPV)	*Description of the method:* [3, 6, 7, 8, 9] *Application:* [3, 6, 7, 8, 9, 10] *Case studies:* concrete diagnosis [7], research for method improvement [11]
		Acoustic emission (AE)	*Description of the method:* [6, 12] *Application:* [6, 12] *Case studies:* research for method improvement [6, 12]
		Impact-Echo (IE)	*Description of the method:* [13, 14, 15] *Application:* [13, 14, 15] *Case studies:* research for method improvement [13]
		Impulse-Response	*Description of the method:* [8, 14, 15] *Application:* [8, 14] *Case studies:* concrete diagnosis [8]
		Ultrasonic Echo	*Description of the method:* [8, 16, 17, 18, 19, 20] *Application:* [8, 16, 17] *Case studies:* concrete diagnosis [21, 22], research for method improvement [18]
	Based on imaging technologies	Infrared thermography (IRT)	*Description of the method:* [23, 24, 25, 26, 27] *Application:* [23, 24, 25] *Case studies:* concrete diagnosis [24, 25], research for method improvement [25, 26, 27]
		Radiography testing (RT)	*Description of the method:* [28, 29] *Application:* [28, 29]
		Others	Optical NDT (Fiber Optics, Electronic Speckle) [24], Imaging techniques (Shearography) [30]
Evaluation of steel reinforcement corrosion	*Chloride testing*	Rapid chloride content and profiling	*Description of the method:* [8, 31] *Application:* [8, 31] *Case studies:* concrete diagnosis [32]
		Others	Chloride titrator test strips, Potentiometric titration [3], Sweep Frequency Technique (SFT) [6]
	Percentage of corrosion, corrosion rate and progress	Half-cell potential (HCP)	*Description of the method:* [8, 33, 34] *Application:* [8, 33, 34]
		Galvanostatic pulse method	*Description of the method:* [8, 35] *Application:* [8, 35] *Case studies:* concrete diagnosis and research for method improvement [35]
		Electrical resistivity (ER)	*Description of the method:* [34, 36, 37] *Application:* [34, 36, 37] *Case studies:* concrete diagnosis [36], research for method improvement [37, 38]
		Others	Linear Polarization Resistance (LPR), Electrochemical Impedance Spectroscopy (EIS) [39], Combined methodology of GPR and IRT [23],
			Active electrochemical, ion mobility and passivation (AECIP) testing [40]
	Carbonation depth, pH of concrete	Phenolphthalein indicator	*Description of the method:* [8, 41] *Application:* [8, 41] *Case studies:* concrete diagnosis [42]
		Rainbow indicator	*Description of the method:* [8, 43] *Application:* [8] *Case studies:* concrete diagnosis [42]
Determination of in-place compressive strength, surface hardness and adhesion		Rebound hammer (RH)	*Description of the method:* [33, 34, 44, 45, 46] *Application:* [34, 44, 45] *Case studies:* concrete diagnosis [44], research for method improvement [11, 43]
		Pull-out test	*Description of the method:* [8, 45, 47] *Application:* [8, 45]
		Pull-off test	*Description of the method:* [8, 30] *Application:* [8, 48] *Case studies:* research for method improvement [30, 48]
		Maturity	*Description of the method:* [49, 50, 51] *Application:* [49, 50]
Determination of concrete cover, rebar diameter, location of steel reinforcement		Ground penetrating radar (GPR)	*Description of the method:* [1, 38, 52, 6] *Application:* [1, 38, 52]
		Covermeters	*Description of the method:* [53] *Application:* [53, 4] *Case studies:* concrete diagnosis and research for method improvement [53]
Evaluation of permeability		Water penetration test	*Description of the method:* [8, 54] *Application:* [8, 55] *Case studies:* concrete diagnosis [54, 56]
		Moisture content	*Description of the method:* [8] *Application:* [2]
		Others	Moisture content in concrete, thermal analysis, gamma ray method, ultrasonic techniques, X-ray diffraction and scanning electron microscopy [2], Novel sensing technique using a smart antenna for the non-destructive evaluation of moisture content and deterioration in concrete blocks [2], Microwave-based SFT used for the detection of water infiltration for concrete roof structures [6]

Evaluation of permeability	Water penetration test	*Description of the method:* [8, 54] *Application:* [8, 55] *Case studies:* concrete diagnosis [54, 56]
	Moisture content	*Description of the method:* [8] *Application:* [2]
	Others	Moisture content in concrete, thermal analysis, gamma ray method, ultrasonic techniques, X-ray diffraction and scanning electron microscopy [2]. Novel sensing technique using a smart antenna for the non-destructive evaluation of moisture content and deterioration in concrete blocks [2]. Microwave-based SFT used for the detection of water infiltration for concrete roof structures [6]
Monitoring of cracks	Petrographic testing	*Description of the method:* [57, 58, 59] *Application:* [57, 58, 59]
	Crack depth and width	*Description of the method:* [8] *Application:* [8] *Case studies:* concrete diagnosis and research for method improvement [39]
	Crack movement	*Description of the method:* [8] *Application:* [8]

defects in plate-like structures, but becomes less effective in detecting smaller, deeper defects in non-plate like structures (e.g. prismatic concrete elements). Also, with the RT method, surface delaminations and small discontinuities are hard or even impossible to detect. The direction of cracks is also important, as cracks that are perpendicular to the radiation are less likely to be detected [28]. Other major disadvantages of the RT method are related to operational safety [29].

NDT challenges can, alternatively, be associated with the analysis of the retrieved data. With the Pull-off method, for instance, test results show large scatter due to the heterogeneous nature of concrete (e.g. presence of coarse aggregates underneath the metallic fixture), or due to variations among experimental conditions (e.g. depth of the partial core); and also, the measured strength may not be representative of the actual bond capacity, since the loading mode will be pure tension, thus, not fully representative of in-situ service conditions [30]. Another case is the UPV method, mainly used to detect flaws but also used to evaluate compressive strength. However, UPV values are affected by several factors, most of which do not necessarily influence the compressive strength of concrete and therefore create noise in the retrieved data [10]. Thus, the use of this method without core testing does not provide reliable predictions of concrete strength. A third example is the GPR technique, which requires a highly skilled specialist to interpret the retrieved data. This complicates the use of the method for SHM and the possibility to monitor structures over a long period of time to predict potential failures, since processing and analyzing such long-term data would be problematic.

Both of the aforementioned types of challenges come along with the ER method. Accurately interpreting ER data is complex, as the values are sensitive to various parameters related to material properties and environmental factors. In fact, the electrical current is carried by the dissolved charged ions flowing through the pore solution in the concrete, so all the factors affecting the pore structure (e.g. w/c ratio, age, cement type, pozzolanic admixtures, degree of hydration…) will also affect its electrical resistivity. Rebar diameter and spacing, rebar orientation with respect to the probe and cover thickness also cause the variation of ER values [37]. Plus, the test tends to be time consuming and often cause public inconveniences.

The two kinds of challenges also appear in the IRT technique. "Passive" IRT under natural excitation sources is dependent on weather conditions, surface orientation, color and texture of the concrete. There are contradictory reports regarding appropriate time windows for testing. The same defect will have time-varying contrast over the course of the day, and hence, understanding the environmental conditions required to provide an adequate thermal gradient is crucial [25]. For that reason, "active" IRT techniques are used more and more for damage detection, establishing a thermal gradient in the tested concrete by importing energy through an artificial external heat source. However, concrete has low thermal conductivity and is thermally inert, so it requires a lot of energy to manipulate its temperature change and initiate heat flow. Plus, non-uniform heating can lead to false positive results. Consequently, complex post-processing is often needed for thermogram analysis [26].

No single method capable of assessing all structural problems exist, and as a result, complementary NDT is essential. By means of the HCP test, for instance, the potentiometer makes no indication of the corrosion rate but only of the probability that corrosion is ongoing [34]. Therefore, additional NDT to evaluate the corrosion progress is needed. Similarly, while Petrographic testing analyzes concrete at a micro level, other NDT methods provide the data required to have a complete understanding of the structural issues. In other words, petrography alone won't be sufficient for a thorough concrete diagnosis [57].

Another example is the RH test. Manufacturers provide means for rebound numbers to be converted into compressive strength values, but these are not universal and are unreliable, unless the results are correlated to semi-destructive (or destructive) test results. Shubbar et al. (2020) suggest that higher values of compressive strength can be obtained because of surface carbonation, which causes concrete hardening. The harder the concrete, the higher the measured compressive strength, which might not be true for concrete at a greater depth. Higher values can also be obtained when spalling has occurred. On the contrary, a surface with a high moisture content will result in a lower rebound number [33]. Additional NDT as a way of backing results up is highly recommended.

On another note, many of the analyzed methods are not entirely non-destructive. With the HCP technique, for instance, it is necessary to open-up the concrete object for the probe to be in contact with the embedded rebar. The results are largely dependent on the effectiveness of electrical contact [34]. Minor surface damage is caused while carrying out Pull-out and Pull-off testing. Petrographic testing requires core extraction.

Challenges faced by NDT methods are not limited to traditional techniques. Modern tools, such as drones, are not exempt from drawbacks [60].

3. A review on the state-of-the-art of concrete NDT methods

Benefited from the remarkable technological advances of recent decades, NDT has experienced major breakthroughs, as continual improvements in their performance and capabilities have been actively pursued. For example, Howlader et al. (2015) proposed a novel magnetic adhesion mechanism for a wall-climbing robot for vertical RC structures [63].

The paper by Kot et al. (2021) summarizes recent advancements in several contemporary NDT techniques for SHM of concrete. Great attention is paid towards artificial intelligence (AI) as an important part of complex data interpretation. The authors comment on the use of deep machine learning to automate the concrete crack detection process. Other modern tools for SHM are also reviewed, such as: Fiber Optic Sensors (FOS), Camera-based techniques for monitoring the displacement of structures, and Laser Scanners, considered as LiDAR (Light Detection and Ranging) or LaDAR (Laser Detection and Ranging) systems, as part of the remote sensing technologies for detailed inspection of large structures [6].

Hüsken et al. (2021) used optical measuring techniques to study the load-bearing behavior of an RC beam. The focus of their work was on determining failure modes by optical NDT and comparing them with classical measuring methods. The bending beam was equipped with two single-mode (SM) sensor fibers. Optical deformation measurements using Digital Image Correlation (DIC) and Stereophotogrammetry (SP) were conducted [64].

Ham et al. (2015) studied the usefulness of micro-electro-mechanical sensors (MEMS) for application in air-coupled (contactless) sensing to concrete NDT. The application of MEMS towards established concrete test methods, including vibration resonance, impact-echo, ultrasonic surface wave and multi-channel analysis of surface waves (MASW) was demonstrated, and in each test application, the performance of MEMS was compared with conventional contactless and contact sensing technology [65].

Milovanović et al. (2016) pointed out how advances in signal processing, together with efficient numerical algorithms and increased access to powerful computers made it feasible to successfully implement imaging technology into NDT of concrete structures [25].

Yet, the availability of cutting-edge technology is not enough. A proper interpretation of the retrieved data is just as important. Researchers are investigating AI techniques, namely machine learning (ML) algorithms, artificial neural networks (ANNs), support vector machines (SVM), adaptive neural fuzzy inference systems (ANFIS)… to address various challenges, and also combining multiple non-destructive techniques to improve the accurateness and facilitate the obtainment of additional parameters, to enhance the diagnosis process.

Lande and Gadewar (2012) studied how the use of AI, specifically ANN techniques, is a viable strategy to develop computational tools that support the interpretation of ultrasonic methods, to reduce bias and help specialists with analyzing the great amount of test data [10].

Due to the fact that by means of the RH test and the UPV test, concrete compressive strength estimations have a large percentage of error when compared to the results of destructive tests, Ngo et al. (2021) used AI techniques (i.e. ANNs, SVM and ANFIS) to explore the relationships between the results from the two NDT tests and concrete strength [9].

Zhang et al. (2016) introduced advanced ML techniques for data analysis and interpolation of the IE method, based on the idea that the features extracted from the raw IE signals carry much richer information for capturing the IE signal patterns than the peak frequency shift used in the traditional method [13].

Researchers often combine the results of complementary NDT methods. Moczko et al. (2014) described how the Impulse-Response method can be used for fast screening of large concrete structures to determine local areas with possible flaws for further detailed analysis. Such is also the case for the IRT technique, for which researchers have carried out extensive laboratory and in-situ testing comparing its results with the ones from electromagnetic and ultrasonic methods. Milovanović et al. (2016) summarized numerous case studies where the fusion of two or more NDT methods improved the reliability of the assessment [25].

Moreover, NDT is essential in the world of research itself. Rathnarajan et al. (2017), for example, investigated carbonation rate and service life of RC systems with mineral admixtures and special cements, using the Phenolphthalein and Rainbow indicators [42].

Lastly, a fundamental problem in NDT is that the knowledge on the matter is radically heterogeneous around the world. Ten years ago, Lee et al. (2012) presented an in-depth study on the usage of NDT methods in the USA. They aimed at clarifying how, when, and where state Departments of Transportation used NDT methods for highway bridge inspections [66]. Their findings were substantially positive. On the other hand, three years ago, Martínez-Barrita et al. (2019) pointed out that the use of semi-destructive and NDT techniques in some parts of Mexico was very limited, like in Oaxaca, where their study took place [67].

For further information, extensive bibliographic reviews about NDT were also previously carried out by Verma et al. (2013) [3] and by Venkatesh et al. (2017) [43].

3.1 Standardization of NDT methods

NDT techniques have been used for decades, and at present, over 70 types of standardized methods can be used for concrete evaluation [68].

Verma et al. (2013) present a broad list of codes describing NDT methods, as part of their "Review of Nondestructive Testing Methods for Condition Monitoring of Concrete Structures" [3]. Kwan et al. (2015) also list several local and foreign reference standards for condition assessment [34]. Moczko et al. (2018) comment on the new European standard approach introduced for traditional concrete quality control (laboratory testing), a group of standards specified as EN

12390; and for testing concrete in existing structures (in-situ measurements), a group of standards specified as EN 12504 [45]. Nevertheless, even when some national and international codes of practice already incorporate NDT methods, this is still a work in progress with a long way to go.

3.2 Future outlook for NDT methods

Civil engineering as a whole is being revolutionized by tools like remote sensing, AI, the Internet of Things, optical fiber, sensors, drones, high-definition imaging tools, battery-pocket-sized computers… Hence, it is foreseeable that a bright future expects NDT. Efforts are oriented towards modeling the life of structures, processing long-term monitoring data, extracting in-depth information about material properties, enhancing the combination of complementary methods, identifying imperceptible deterioration levels, increasing ease-of-use, accuracy, efficiency; establishing traceable procedures with minimal effort and enabling unobstructed data sharing for collaboration and quality assurance of critical infrastructure [52].

Investigation towards NDT innovation is ongoing. At the end of their article, Zatar et al. (2020) anticipate that their future works will be focused on developing a climbing robot to automate the data collection process for the Ultrasonic Echo testing method, and that the software developed in their study will be extended to provide real-time visualization of concrete structures [18]. Chakraborty et al. (2019) point out that the effectiveness of ultrasonic sensors for long term cracking monitoring in real structures will be the focus of their further studies [68]. Sarker et al. (2017) conclude that even though research into the potential of ZED depth camera is still at a basic stage, experimental methods have enormous potential for infrastructure recognition and modeling. Thus, future works will focus on developing a solid framework for more sophisticated modelling techniques [62]. Needless to say, overcoming the current challenges and reaching a comprehensive standardization of these techniques, will lead to progressively wider use of the methods among researchers, technicians and engineers around the world, making it possible to routinely carry out rapid, cost-efficient, straightforward, accurate and reliable concrete diagnosis; and perhaps, substituting completely the need for destructive test methods.

4. Conclusions

Even when the methods that were reviewed on this article have been in general widely and successfully used along the past decades, there are still great challenges that must be overcome if NDT is to become an everyday part of the diagnosis of concrete structures. Neither the tools used for testing, nor the result interpretation techniques are faultless. Additional research is required, and standardization is essential. However, it is fair to say that the limitations certainly do not exceed the advantages, and that as of today, NDT techniques are a fundamental and extremely valuable tool in civil engineering.

This research was supported by Erasmus+ Program (Grant No. 101/STT/2020)

5. References

[1] M. Alsharqawi, T. Zayed and S. Abu Dabous, "Common practices in assessing conditions of concrete bridges," MATEC Web of Conferences 120, 02016 (2017), DOI: 10.1051/matecconf/201712002016, 2017.

[2] K. H. Teng, P. Kot, M. Muradov, A. Shaw, K. Hashim, M. Gkantou and A. Al-Shamma'a, "Embedded Smart Antenna for Non-Destructive Testing and Evaluation (NDT&E) of Moisture Content and Deterioration in Concrete," Sensors 2019, 19, 547; doi:10.3390/s19030547, 2019.

[3] S. K. Verma, S. S. Bhadauria and S. Akhtar, "Review of Nondestructive Testing Methods for Condition Monitoring of Concrete Structures," Journal of Construction Engineering, Hindawi Publishing Corporation, vol. 2013. Article ID 834572.

[4] Industrial Applications and Chemistry Section, International Atomic Energy Agency (IAEA), Guidebook on non-destructive testing of concrete structures. Training Course Series No. 17, Vienna: Printed by the IAEA in Austria, September 2002.

[5] N. J. Carino, "Nondestructive Testing of Concrete: History and Challenges," SP-144: Concrete Technology: Past, Present, and Future, American Concrete Institute, DOI:10.14359/4456, pp. 623-678, 1994.

[6] P. Kot, M. Muradov, M. Gkantou, G. . S. Kamaris, K. Hashim and D. Yeboah, "Recent Advancements in Non-Destructive Testing Techniques for Structural Health Monitoring," Applied Sciences 2021, 11, 2750, 2021.

[7] L. Pedreros, F. Cárdenas, N. Ramírez and E. Forero, "NDT Non-Destructive Test for Quality Evaluation of Concrete specimens by Ultrasonic Pulse Velocity measurement," IOP Conf. Series: Materials Science and Engineering 844 (2020) 012041, 2020.

[8] Germann Instruments, "Products by Application," [Online]. Available: https://germann.org/products-by-application. [Accessed March 2022].

[9] T. Q. L. Ngo, Y. R. Wang and D. L. Chiang, "Applying Artificial Intelligence to Improve On-Site Non-Destructive Concrete Compressive Strength Tests," Crystals 2021, 11, 1157. https://doi.org/10.3390/cryst11101157, 2021.

[10] P. S. Lande and A. S. Gadewar, "Application of Artificial Neural Networks in Prediction of Compressive Strength of Concrete by Using Ultrasonic Pulse Velocities," IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE). ISSN: 2278-1684, vol. 3, no. 1, pp. 34-42, Sep-Oct. 2012.

[11] B. Youcef, K. Said and A.-B. Khoudja, "Prediction of concrete strength by non-destructive testing in old structures: Effect of core number on the reliability of prediction," MATEC Web of Conferences 149, 02007 (2018), CMSS-2017, https://doi.org/10.1051/matecconf/201814902007, 2018.

[12] T.-M. Oh, M.-K. Kim, J.-W. Lee, H. Kim and M.-J. Kim, "Experimental Investigation on Effective Distances of Acoustic Emission in Concrete Structures," Applied Sciences 10, 6051, 2020.

[13] J. K. Zhang, W. Yan and D. M. Cui, "Concrete Condition Assessment Using Impact-Echo Method and Extreme Learning Machines," Sensors 2016, 16, 447; doi:10.3390/s16040447, 2016.

[14] A. Moczko and M. Moczko, "Modern NDT Systems for Structural Integrity Examination of Concrete Bridge Structures," Procedia Engineering 91, XXIII R-S-P seminar, Theoretical Foundation of Civil Engineering (23RSP) (TFoCE 2014), doi: 10.1016/j.proeng.2014.12.086, p. 418 – 423, 2014.

[15] A. G. Davis, "Impact-Echo and Impulse Response Testing," Workshop on new technologies for NDT of roads and bridges, 1998 Transportation Research Board Annual Conference, January 1998.

[16] S. Küttenbaum, A. Taffe, T. Braml and S. Maack, "Reliability assessment of existing bridge constructions based on results of non-destructive testing," MATEC Web of Conferences 199, 06001 (2018), https://doi.org/10.1051/matecconf/201819906001, 2018.

[17] O. Aguirre, I. Vidaud, L. Peña and E. Vidaud, "Evaluación de Integridad Estructural mediante Tomografía Tridimensional Ultrasónica (MIRA), Primera parte," Construcción y Tecnología en Concreto, June 2013.

[18] W. A. Zatar, H. D. Nguyen and H. M. Nghiem, "Ultrasonic pitch and catch technique for non-destructive testing of reinforced concrete slabs," Journal of Infrastructure Preservation and Resilience, https://doi.org/10.1186/s43065-020-00012-z, 2020.

[19] O. Aguirre, I. Vidaud, L. Peña and E. Vidaud, "Evaluación de Integridad Estructural mediante Tomografía Tridimensional Ultrasónica (MIRA), Segunda parte," Construcción y Tecnología en Concreto, July 2013.

[20] C. Germann Petersen and H. D. Orozco Recillas, "Non-destructive testing of joints in precast element structures," Concrete Solutions: Proceedings of Concrete Solutions, 6th International Conference on Concrete Repair, Thessaloniki, Greece. ISBN 978-1-138-03008-4, pp. 229-234, 2016.

[21] E. Krawczyk, "Praca Dyplomowa Magisterska: Analiza wybranych metod nieniszczących do badania konstrukcji betonowych dostępnych jednostronnie (in Polish)," Politechnika Wrocławska, Wrocław, Academic Year 2019/2020.

[22] A. Kwiecińska, "Master's Diploma Thesis: Analysis of selected non-destructive methods for concrete diagnosis," Politechnika Wrocławska, Wrocław, Academic Year 2017/2018.

[23] M. Solla, S. Lagüela, N. Fernández and I. Garrido, "Assessing Rebar Corrosion through the Combination of Nondestructive GPR and IRT Methodologies," Remote Sensing 2019, 11, 1705; doi:10.3390/rs11141705, 2019.

[24] Y. K. Zhu, G. Y. Tian, R. S. Lu and H. Zhang, "A Review of Optical NDT Technologies," Sensors 2011, 11, 7773-7798; doi:10.3390/s110807773, ISSN 1424-8220, 2011.

[25] B. Milovanović and I. Banjad Pečur, "Review of Active IR Thermography for Detection and Characterization of Defects in Reinforced Concrete," Journal of Imaging 2016, 2, 11; doi:10.3390/jimaging2020011, 2016.

[26] B. Milovanović, M. Gaši and S. Gumbarević, "Principal Component Thermography for Defect Detection in Concrete," Sensors 2020, 20, 3891; doi:10.3390/s20143891, 2020.

[27] J. Huh, V. H. Mac, Q. H. Tran, K. Y. Lee, J. I. Lee and C. Kang, "Detectability of Delamination in Concrete Structure Using Active Infrared Thermography in Terms of Signal-to-Noise Ratio," Applied Sciences 2018, 8, 1986; doi:10.3390/app8101986, 2018.

[28] S. Nasrazadani and S. Hassani, "Modern analytical techniques in failure analysis of aerospace, chemical, and oil and gas industries," in Handbook of Materials Failure Analysis with Case Studies from the Oil and Gas Industry, First Edition, Elsevier, 2016.

[29] VicRoads, "Technical Note: Non-Destructive Testing (NDT) of Concrete in Structures," December 2010. [Online]. Available: https://www.vicroads.vic.gov.au. [Accessed April 2022].

[30] A. Billon-Filiot, F. Taillade, M. Quiertant, J. M. Hénault, J. C. Renaud, R. Maurin and K. Benzarti, "Development of an Innovative Non-Destructive and Field-Oriented Method to Quantify the Bond Quality of Composite Strengthening Systems on Concrete Structures," Materials 2020, 13, 5421; doi:10.3390/ma13235421, 2020.

[31] E. Poulsen, "Chloride Profiles: Analysis and Interpretation of Observations," AEClaboratory, 1995.

[32] L. O. Nilsson, "Durability concept; pore structure and transport processes," in Advanced Concrete Technology, Elsevier, 2003.

[33] A. A. Shubbar, Z. S. Al-khafaji, M. S. Nasr and M. W. Falah, "Using non-destructive tests for evaluating flyover footbridge: Case study," KBES, 2020.

[34] A. Kwan and P. L. Ng, "Building Diagnostic Techniques and Building Diagnosis: The Way Forward," P.W. Tse et al. (eds.), Engineering Asset Management - Systems, Professional Practices and Certification, Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-09507-3_74, pp. 849-862, November 2015.

[35] S. Sathiyanarayanan, P. Natarajan, K. Saravanan, S. Srinivasan and G. Venkatachari, "Corrosion monitoring of steel in concrete by galvanostatic pulse technique," Cement & Concrete Composites 28 (2006), doi:10.1016/j.cemconcomp.2006.03.005 , pp. 630-637, 2006.

[36] K. Hornbostel, T. Danner and M. R. Geiker, "Non-destructive Test Methods for Corrosion Detection in Reinforced Concrete Structures," Nordic Concrete Research – Publ. No. NCR 62 – Article 3, DOI: 10.2478/ncr-2019-0005, no. 1, pp. 41-61, 2020.

[37] K. P. V. Robles, J.-J. Yee and S.-H. Kee, "Effect of the Geometrical Constraints to the Wenner Four-Point Electrical Resistivity Test of Reinforced Concrete Slabs," Sensors 2021, 21, 4622. https://doi.org/10.3390/s21134622, 2021.

[38] Z. M. Sbartaï, S. Laurens, J. Rhazi, J. P. Balayssac and G. Arliguie, "Using radar direct wave for concrete condition assessment: Correlation with electrical resistivity," Journal of Applied Geophysics 62 (2007), doi:10.1016/j.jappgeo.2007.02.003, p. 361–374, 2007.

[39] J. H. Castorena-González, U. Martin, C. Gaona-Tiburcio, R. E. Núñez-Jáquez, F. M. Almeraya-Calderón, J. M. Bastidas and D. M. Bastidas, "Modeling Steel Corrosion Failure in Reinforced Concrete by Cover Crack Width 3D FEM Analysis," Frontiers in Materials, doi: 10.3389/fmats.2020.00041, vol. 7, no. 41, February 2020.

[40] R. W. Arndt, "Next Generation Building Diagnostics – Corrosion Detection," in Fifth International Conference on Sustainable Construction Materials and Technologies (SCMT5), London, 2019.
[41] V. Rimshin and P. Truntov, "Determination of carbonation degree of existing reinforced concrete structures and their restoration," E3S Web of Conferences 135, 03015 (2019), ITESE-2019, https://doi.org/10.1051/e3sconf/201913503015, 2019.
[42] S. Rathnarajan and R. G. Pillai, "Carbonation rate and service life of reinforced concrete systems with mineral admixtures and special cements," in CORCON, Mumbai, September 2017.
[43] P. Venkatesh and M. Alapati, "Condition Assessment of Existing Concrete Building Using Non-Destructive Testing Methods for Effective Repair and Restoration - A Case Study," Civil Engineering Journal, http://dx.doi.org/10.28991/cej-030919, vol. 3, no. 10, October 2017.
[44] A. Borosnyói, "NDT Assessment of existing concrete structures: Spatial analysis of rebound hammer results recorded in-situ," Engineering Structures and Technologies, ISSN 2029-882X / eISSN 2029-8838, 2015 7(1), doi:10.3846/2029882X.2015.1085331, pp. 1-12, 2015.
[45] A. Moczko and M. Moczko, "In-situ examination of the concrete quality: European standard approach," MATEC Web of Conferences 196, 02045 (2018), XXVII R-S-P Seminar 2018, Theoretical Foundation of Civil Engineering, https://doi.org/10.1051 /matecconf/201819602045, 2018.
[46] Technischen Universität München (TUM), "TUM Wiki-System," [Online]. Available: https://wiki.tum.de/. [Accessed April 2022].
[47] N. J. Carino, "In-Place Strength Without Testing Cores: The Pullout Test," in 6th International Seminar on Advances in Cement & Concrete Technology for Sustainable Development.
[48] S. Czarnecki, "Non-destructive evaluation of the bond between a concrete added repair layer with variable thickness and a substrate layer using ANN," Procedia Engineering 172 (2017), doi: 10.1016/j.proeng.2017.02.049, p. 194–201, 2017.
[49] N. J. Carino and H. S. Lew, "The Maturity Method: From Theory to Application," in Proceedings of the 2001 Structures Congress & Exposition, Washington, D.C., 2001.
[50] COMMAND Center concrete temperature and maturity system, "The Maturity Method: Why You Should Validate Your Maturity Curve," June 2019. [Online]. Available: https://www.commandcenterconcrete.com/maturity-method-why-validate-maturity-curve/. [Accessed May 2022].
[51] BERRA Construction Products, "What Is Concrete Maturity?," [Online]. Available: https://www.berraproducts.com.au/what-is-concrete-maturity/. [Accessed May 2022].
[52] O. G. Erhimona and J. Andrew, "Recent advances in non-destructive testing of concretes and structures: An outlook," Journal of Civil Engineering and Construction Technology, DOI: 10.5897/JCECT2019.0494, pp. 20-31, 2019.
[53] N. J. Carino, "Performance of Electromagnetic Covermeters for Nondestructive Assessment of Steel Reinforcement," NISTIR 4988, National Institute of Standards and Technology, December 1992.
[54] A. Moczko and M. Moczko, "GWT – New Testing System for „in-situ" Measurements of Concrete Water Permeability," Procedia Engineering 153 (2016), XXV Polish – Russian – Slovak Seminar "Theoretical Foundation of Civil Engineering", p. 483–489, 2016.
[55] A. I. Cark, "The Influences of Silica Fume and Curing Temperature on Water Permeability of Concrete," [Online]. Available: https://www.germanninstruments.com/wp-content/uploads/2022/01/Cark-A.-I.-The-influence-of-silica-fume-and-curing-temperature-on-water-permeability-of-concrete.pdf. [Accessed May 2022].
[56] K. G. Trezos, I. P. Sfikas and D. I. Pavlou, "Water Permeability of Self Compacting Concrete," 3rd fib International Congress, 2010.
[57] D. Rothstein, "Petrography: What It Can and Cannot Do," AC Business Media, Inc. Construction Network, January 2014. [Online]. Available: https://www.forconstructionpros.com/concrete/article/11248215/petrography-what-it-can-and-cannot-do-for-concrete-contractors. [Accessed April 2022].
[58] "Petrographic Examination of Concrete," Concrete Research & Testing, LLC (CRT), [Online]. Available: http://www.concretetesting.com/petrographic-examinations-concrete/. [Accessed April 2022].
[59] A. Snyder, "What Can Petrographic Analysis Tell You About the Condition of Concrete Structures?," RJ Lee Group, December 2014. [Online]. Available: https://www.rjlg.com/2014/12/petrography-tell-you-about-concrete-structures/. [Accessed April 2022].
[60] E. Ciampa, L. De Vito and M. R. Pecce, "Practical issues on the use of drones for construction inspections," XXVI AIVELA National Meeting, IOP Conf. Series: Journal of Physics: Conf. Series 1249 (2019) 012016, doi:10.1088/1742-6596/1249/1/012016, 2019.
[61] Vlaamse Drone Federatie (EUKA), Wetenschappelijk en Technisch Centrum voor het Bouwbedrijf (WTCB), Vlaams agentschap Innoveren & Ondernemen (VLAIO), "Drones als hulpmiddel: Inzichten in nieuwe werkprocessen op de bouwwerf (Drones as a tool: Insights into new work processes on the construction site)," VIS-project, in Dutch, January 2020.
[62] M. M. Sarker, T. A. Ali, A. Abdelfatah, S. Yehia and A. Elaksher, "A Cost-Effective Method for Crack Detection and Measurement on Concrete Surface," The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W8, 5th International Workshop LowCost 3D – Sensors, Algorithms, Applications, Hamburg, Germany, November 2017.
[63] O. F. Howlader and T. P. Sattar, "Finite Element Analysis based Optimization of Magnetic Adhesion Module for Concrete Wall Climbing Robot," International Journal of Advanced Computer Science and Applications (IJACSA), vol. 6, no. 8, 2015.
[64] G. Hüsken, S. Pirskawetz, D. Hofmann, F. Basedau, K. P. Gründer and D. Kadoke, "The load-bearing behavior of a reinforced concrete beam investigated by optical measuring techniques," Materials and Structures (2021) 54:102, https://doi.org/10.1617/s11527-021-01699-6, 2021.

[65] S. Ham and J. S. Popovics, "Application of Micro-Electro-Mechanical Sensors Contactless NDT of Concrete Structures," Sensors 2015, 15; doi:10.3390/s150409078, pp. 9078-9096, 2015.

[66] S. Lee and N. Kalos, "Bridge inspection practices using non-destructive testing methods," Journal of Civil Engineering and Management, 2015, ISSN 1392-3730 / eISSN 1822-3605, vol. 21(5), p. 654–665, 2015.

[67] R. Martínez-Barrita, H. López-Calvo, H. Gómez-Barranco and A. Muciño-Vélez, "Diagnosis of the deterioration state of a reticular reinforced concrete roof using non-destructive and semi-destructive techniques," Revista de Ingeniería Civil, vol. 3, no. 7, pp. 12-20, March 2019.

[68] J. Chakraborty, A. Katunin, P. Klikowicz and M. Salamak, "Early Crack Detection of Reinforced Concrete Structure Using Embedded Sensors," Sensors 2019, 19, 3879; doi:10.3390/s19183879, 2019.

[69] S. A. Rizwan, M. A. Qureshi and F. A. Najam, "In-Situ Health Assessment of a Poorly Executed Pre-Stressed In-Service Concrete Bridge and Suggesting a Rehabilitation Strategy – a Case Study," Procedia Engineering 54 (2013), doi: 10.1016/j.proeng.2013.03.058, pp. 636-647, 2013.