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Non-destructive and semi-destructive diagnostics of concrete structures in assessment of their durability

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Abstract. This paper proposes a comprehensive classification of test methods for the diagnosis of concrete structures. The main focus is on the ranges of suitability of the particular methods and techniques for assessing the durability of structures, depending on the principal degradation mechanisms and their effects on this durability. The survey covers non-destructive testing (NDT) methods, which do not in any way breach the integrity of the tested structures, and semi-destructive testing (SDT) methods requiring material samples to be taken or any other minor breach of structural integrity. An original taxonomy of physical, chemical and biological diagnostic methods, useful in assessment of concrete structures durability, is proposed. Equipment specific for selected advanced testing methods is presented as well as exemplary test results.

Key words: concrete, durability, diagnostics, non-destructive tests, semi-destructive tests.

1. Introduction

The durability of concrete structures is determined on the one hand, by the type and intensity of the degradation mechanisms acting on it and on the other hand, by its resistance to degrading physical factors (rheological processes, freeze/thaw actions, erosion, crystallization, leaching, overloading, fatigue, temperature and humidity influence), mechanisms connected with chemical phenomena (carbonization, corrosion, aggressive environmental impact, reactions between material components) and biological mechanisms caused by the action of living organisms (microorganisms, plants, animals) on the concrete structure [1–4].

As a rule, combinations of the different mechanisms, in the form of complex degradation processes causing damage to the structure and ultimately determining its service life, occur in practice. The principal phenomena influencing durability include: changes in structure geometry (deformations and displacements, changes in component dimensions, etc.), modifications of material macro- and microstructure, fluctuations of material mechanical parameters, development of material discontinuities (cracks, fractures, delaminations, etc.), fluctuations of material resistance to water and gases penetration as well as changes in the chemical constitution of the material. The dependences between the principal degradation mechanisms and the factors having a significant bearing on the determination of the durability of concrete structures are presented in Table 1.

Table 1
Phenomena influencing durability of concrete structures, caused by principal degradation mechanisms

Degradation mechanisms	Phenomena influencing durability					
	Structure geometry	Material macro- & microstructure	Mechanical parameters of material	Discontinuity of material	Water & gases resistance	Chemical constitution
Rheological processes	■	■	■	■	□	–
Freeze/thaw actions	□	■	■	■	■	–
Erosion	□	□	–	–	–	–
Crystallization	–	■	■	□	□	□
Leaching	–	□	■	–	■	■
Overloading	■	□	□	■	–	–
Fatigue	–	■	■	□	–	–
Temperature influence	■	□	–	□	–	□
Humidity influence	–	■	■	□	■	□
Carbonization	–	–	□	–	□	■
Corrosion	□	■	■	□	□	■
Aggressive environmental impact	–	□	□	–	□	■
Reactions between material components	–	■	■	□	□	■
Living organisms influence	–	□	–	□	–	■

■ – fundamental influence, □ – additional influence, – not applicable.

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In the further part of this paper an innovative comprehensive classification of the investigative methods and techniques used in the diagnosis of the durability of concrete structures is proposed. Non-destructive testing (NDT) methods, which do not in any way breach the integrity of the tested structure, and semi-destructive testing (SDT) methods requiring material samples to be taken or any other minor breach of structure integrity, have been distinguished.

2. Taxonomy of NDT methods

2.1. Classification criteria. Figure 1 shows a proposal of general division of the non-destructive test methods useful in assessing the durability of structures made of concrete. Some of the methods are listed below while Table 2 shows an original arrangement of the factors having a significant influence on the durability of concrete structures, with suitable methods of their identification assigned to them.

2.2. Optical methods. According to the classification shown in Fig. 1, the group of optical methods suitable for assessing the durability of plane concrete as well as reinforced and prestressed concrete structures includes many measuring techniques using such test equipment as: microscopes, endoscopes, borescopes (Fig. 2a), videoscopes (Fig. 2b), specialist geodetic equipment, tv cameras etc. [1, 4, 5].

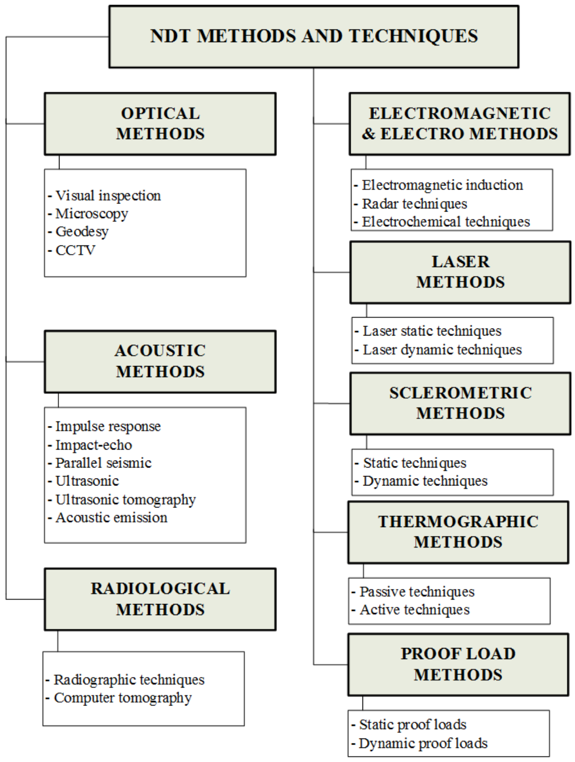

Fig. 1. Basic non-destructive testing (NDT) methods and techniques useful in assessing concrete structure durability

Table 2
Phenomena influencing durability of concrete structures, identified by means of NDT methods

NDT methods	Phenomena influencing durability					
	Structure geometry	Material macro- & microstructure	Mechanical parameters of material	Discontinuity of material	Water & gases resistance	Chemical constitution
Visual inspection	■	■	■	■	□	–
Microscopy	–	■	□	■	□	–
Geodesy	■	–	–	–	–	–
CCTV	□	□	–	□	–	–
Impulse response	–	■	■	–	–	–
Impact echo	■	■	–	■	–	–
Parallel seismic	■	■	–	■	–	–
Ultrasonic	■	■	■	■	–	–
Ultrasonic tomography	■	■	–	□	–	–
Acoustic emission	–	□	–	■	–	–
Radiographic techniques	■	■	–	■	–	–
Computer tomography	■	■	–	■	–	–
Electromagnetic induction	■	–	–	–	–	–
Radar techniques	■	■	–	■	–	–
Laser static techniques	■	–	–	–	–	–
Laser dynamic techniques	■	–	–	–	–	–
Sclerometric static techniques	–	□	■	–	–	–
Sclerometric dynamic techniques	–	□	□	–	–	–
Thermographic passive techniques	–	□	–	□	–	–
Thermographic active techniques	–	□	–	□	–	–
Static proof loads	–	–	□	–	–	–
Dynamic proof loads	–	–	□	□	–	–

■ – basic method, □ – additional method, – not applicable

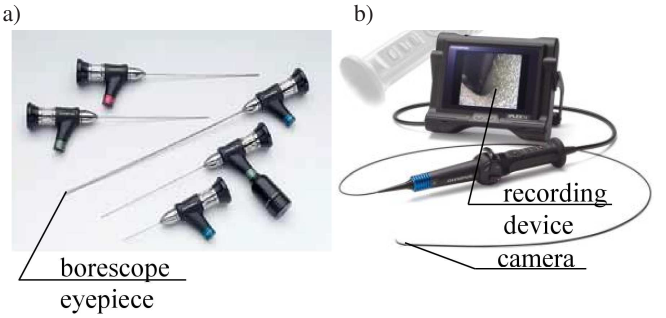

Fig. 2. Borescopes (a) and videoscopes (b) for visual inspections (Ref. 5)

In recent years rapid advances in non-destructive 3D optical methods have been made. Using such methods one can obtain a 3D image of the surface of concrete [6–10]. Analysing the image by means of dedicated computer programs one can generate, e.g., the values of 3D roughness parameters in accordance with ISO 25178 [11]. The parameters are useful in assessing, among other things, the pull-off adhesion of layers in layered structural elements such as floors, where this adhesion has a direct bearing on their durability. This group also includes the laser triangulation method which uses 3D scanners (Fig. 3) to examine surface morphology. The entire surface of an element or its selected parts can be scanned.

Fig. 3. 3D equipment for scanning: a) entire element surface, b) selected small areas of surface

2.3. Acoustic methods. From among the acoustic methods useful in assessing the durability of concrete structures, listed in Fig. 1 the latest methods, i.e. impulse-response, impact echo, parallel seismic and ultrasonic tomography, are described below. An extensive survey of the other acoustic methods can be found in, e.g., [1, 12–18].

The impulse response method [19–21]. The method is useful in: detecting voids under concrete and reinforced concrete slabs laid on the ground and delaminations at the interface between layers, locating defective areas and macrostructural concrete inhomogeneities (honeycombing) in massive concrete members (as much as about 1500 mm thick) and controlling the length and continuity of piles. The test set used in this method includes: a special hammer, a geophone and an amplifier with a portable computer (Fig. 4).

In this method an elastic wave is generated in the tested element by striking it with the calibrated rubber-tipped hammer. Measuring points, forming a grid, are spaced at every 1000 mm. The elastic wave signal (with a frequency of up to 1000 Hz) propagating in the element is recorded by the geophone (which does not need to be acoustically coupled with the surface of the tested element) and simultaneously amplified by the amplifier. The recorded signals are processed by dedicated software. The ultimate results of the tests are presented in the form of maps showing the distribution of the values of five characteristic parameters on the surface of the tested element, i.e. average mobility N_{av}, stiffness K_d, mobility slope M_p, mobility times mobility slope $N_{av} \times M_p$ and voids index v. By analysing the maps one can locate a defective area, as shown in Fig. 5 (the defective area is marked with an ellipse).

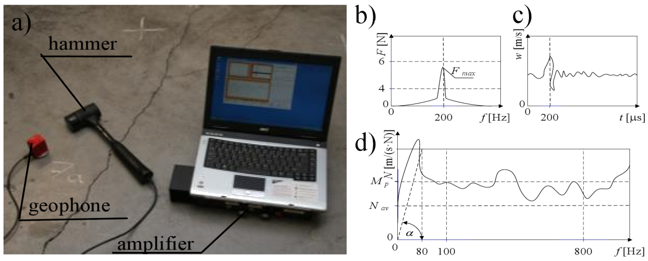

Fig. 4. Impulse response method: a) measuring set, b) diagram of elastic force F generated by hammer, c) diagram of velocity of elastic wave registered by geophone, d) exemplary diagram of mobility N_{av} versus frequency (Ref. 18)

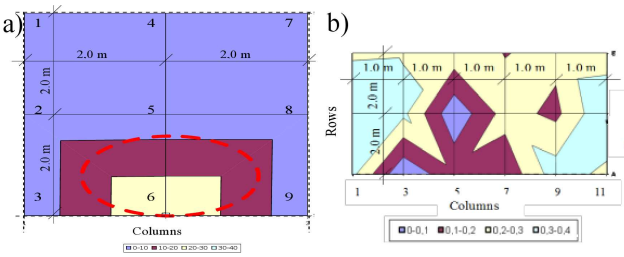

Fig. 5. Exemplary maps of distribution of two characteristic parameters on surface of tested layered concrete element: a) map of mobility N_{av}, b) map of stiffness K_d

The advantage of this method is the high speed of testing large-surface elements with an accuracy depending on the adopted spacing between measuring points.

The impact-echo method. This method is suitable for determining, e.g., the thickness of unilaterally accessible concrete members and detecting defects in up to 800 mm thick members [22]. The method consists in exciting an elastic wave in the tested element by striking its surface (in measuring points spaced at every 100 mm) with an exciter in the form of a steel ball. The frequency of the generated vibrations depends on the diameter of the ball used and amounts to about 10–150 kHz. The dedicated software makes it possible to record (in the amplitude-time system) the image of the elastic wave propagating in the element being tested and subsequently to transform the image into an amplitude-frequency spectrum by means of the Fast Fourier Transform (FFT) or Artificial Neural Networks (ANN). The spectrum is then subjected to a detailed analysis. The measuring set, which includes measuring heads with exciters (steel balls of different diameters) and a portable computer, is shown in Fig. 6. Exemplary results of tests carried out on a damaged post-tensioned concrete girder using this method are shown in Fig. 7.

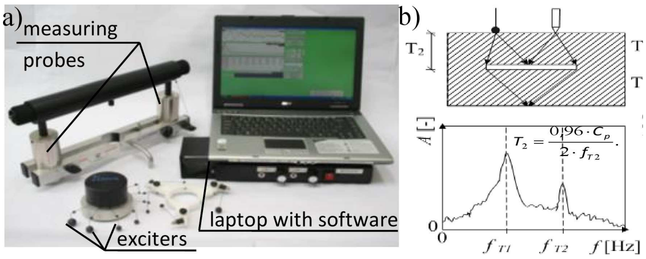

Fig. 6. Impact-echo method: a) measuring set, b) exemplary amplitude-frequency spectrum obtained in case of defect in tested member

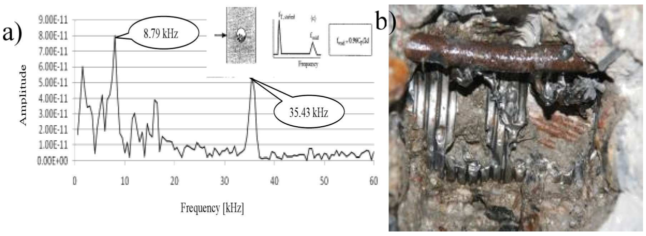

Fig. 7. Exemplary test results: a) amplitude-frequency spectrum of elastic wave in post-tensioned concrete girder recorded by impact-echo equipment, b) indicating cable without cement slurry filling

The advantage of this method is the high accuracy with which defects are located (owing to the dense spacing of measuring points). The disadvantage is that the size of defects filled with water cannot be estimated by this method.

The parallel seismic method. The method belongs to low-energy seismic methods. It is suitable for testing concrete and reinforced concrete foundation piles (both prefabricated and made on site) with regard to their length and cross-sectional continuity along the length [23]. This method requires that a hole should be made in the ground along the tested element, extending to a depth below the expected length of the latter. A hydrophone, operating in a frequency range close to 40 kHz, is placed in the hole and the pile head or the pile cap is struck with a calibrated hammer. As the hydrophone moves in the hole along the pile the time in which the acoustic wave travels from the pile to the hydrophone is recorded after each hammer strike. The wave travel time is analysed using dedicated software to determine the length of the pile and its cross-sectional continuity. Figure 8 shows the measuring set used in the parallel seismic method and an exemplary pile testing scheme.

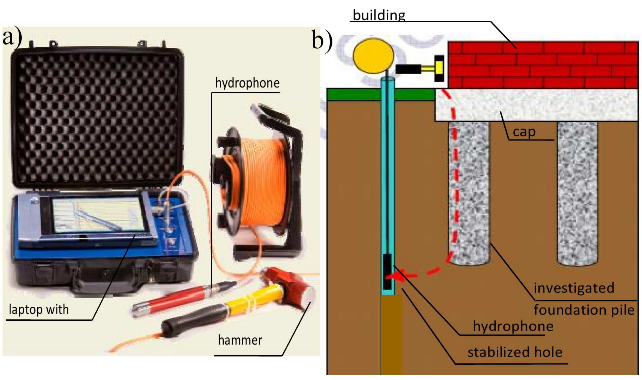

Fig. 8. Parallel seismic method: a) measuring set, b) exemplary pile testing scheme (Ref. 23)

The disadvantage of this method is that a hole should be made in the ground along the tested element, which is not always possible.

The ultrasonic tomography method. This method is one of the latest acoustic methods [24–28]. It is suitable for testing up to 2500 mm thick unilaterally accessible concrete members in order to determine their thickness, detect cracks invisible on the surface, foreign inclusions, air voids or areas filled with a liquid or a material whose physical properties differ from those of the surrounding concrete [25]. The method consists in exciting an elastic wave in the tested member and analysing its image. The exciter is a multihead antenna incorporating tens of spring-fixed independent ultrasonic heads, which is also used for receiving and processing ultrasonic signals. The heads generate ultrasonic pulses with a frequency of 50 kHz. Figure 9 shows an ultrasonic tomograph which includes a special multihead ultrasonic antenna and a laptop with dedicated software for creating graphic images [26]. Three mutually perpendicular images in any cross section and a spatial image of the tested element can be obtained.

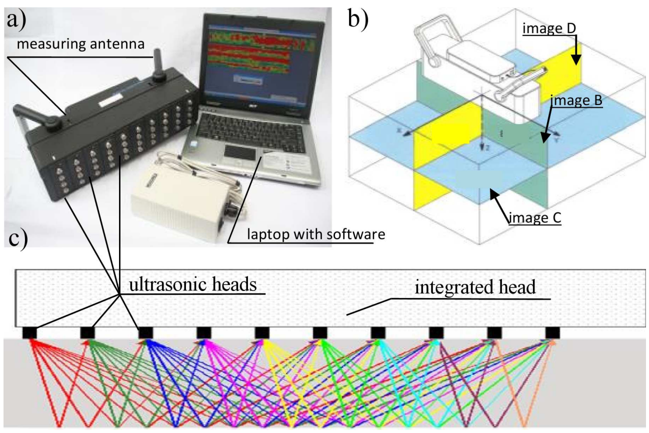

Fig. 9. Ultrasonic tomograph: a) measuring set, b) measuring antenna in coordinate system and possible images, c) schematic of elastic wave excitation by ultrasonic heads

The method does not require any means of coupling the tested element surface with the ultrasonic heads, which is a major advantage. A dry point contact is used instead. Another advantage is the short testing time. The drawback is that the tested element must be at least 500 mm wide.

2.4. Radiological methods. Methods belonging to this group exploit the different attenuation (absorption) of penetrating radiation X or gamma radiation by different materials. This is registered by a detector in the form of silver-gelatin film or by a digital detector in computer radiography (CR) and in direct digital radiography (DR). The methods are described in detail in, e.g., [29]. Today when ultrasonic tomography and radar tomography have appeared, radiological methods are only occasionally used in building practice to test concrete elements.

2.5. Electromagnetic methods. From among the non-destructive electromagnetic methods (Fig. 1) suitable for assessing the durability of concrete structures the latest ground penetrating method (GPR) is described here. GPR is used to determine or detect: thickness, delaminations, large air voids, extensive defects and the location of reinforcement bars in unilaterally accessible concrete and reinforced concrete members [30]. Depending on the purpose for which the radar is used, transmitting/receiving heads (antennas) generate electromagnetic waves with a frequency of 0.1–2.5 GHz. They have wheels and can drive on the surface of tested elements. They are connected via a cable or radio with a data logger. A typical radar set is shown in Fig. 10.

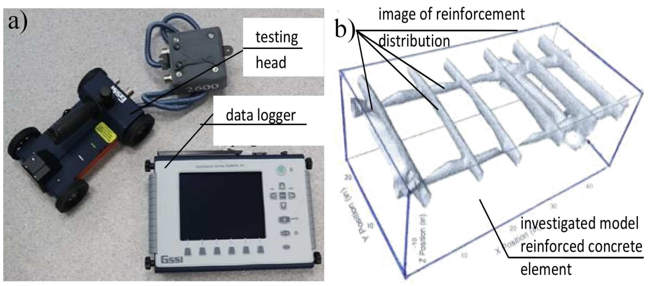

Fig. 10. Radar set (a) and exemplary image showing distribution of reinforcement in representative reinforced concrete element (b)

The advantage of this method is that members with large surfaces can be quickly tested, especially to locate reinforcement. Its disadvantage is the low accuracy of determining reinforcement diameter and concrete cover thickness.

Non-destructive electrochemical techniques, mainly suitable for evaluating the degree of corrosion of the reinforcement in reinforced concrete structures, include the resistance technique [31]. The most popular are the methods of measuring the resistance of the concrete cover, including the non-destructive four-point Wenner method [32]. In recent years modifications of this method have appeared in the literature [33–35]. The method presented in Fig. 11 takes advantage of the short-circuit effect of a steel bar on resistivity rather than avoiding it [36, 37]. Galvanostatic resistivity measurements are taken using a modified electrode array. To ensure the stability of potential during the 30 sec equilibrium period, the two inner standard resistivity probes are replaced with two copper-copper sulphate reference electrodes (Fig. 11a). A small current signal is provided by a standard laboratory galvanostat and the resulting change in potential is measured using a high impedance voltmeter.

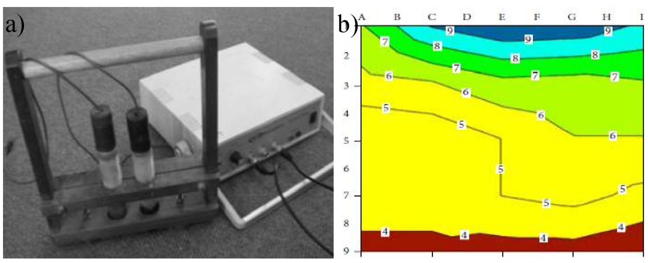

Fig. 11. New corrosion assessing method: a) equipment (Ref. 36), b) exemplary contour plot of concrete resistivity (Ref. 37)

2.6. Laser methods. Non-destructive laser methods are increasingly commonly used to assess the durability of structures made of concrete. Figure 12 shows a typical measuring set used in this method to remotely measure the displacements of whole structures or their parts and the deformations of building structures or their parts over time. The non-contact testing consists in repeated scanning of the spatial form of a building structure over time and comparing the images separated by longer time intervals [38].

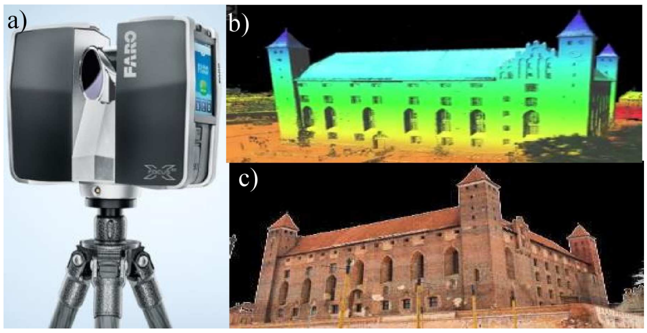

Fig. 12. Measuring set used in laser method (a) and exemplary results: scan of structure (b) and virtual spatial image of structure (c) (Ref. 39)

The advantage of this method is that large building structures can be quickly tested.

2.7. Sclerometric methods. Non-destructive sclerometric methods can be used to determine the hardness and homogeneity of the structure of concrete and the compressive strength of concrete incorporated into structural members and to monitor this strength over time [1, 40, 41]. In the diagnostic practice the dynamic technique currently dominates and the Schmidt sclerometer is a device commonly used for this purpose. In order to determine the compressive strength f_c of concrete built into a given structure it is necessary to work out correlation $f_c - L$, where L is the measured parameter (the rebound number).

2.8. Thermographic methods. Figure 13 shows a typical measuring set used in thermography. It is suitable for, among other things, the qualitative assessment of the continuity of thermal insulation in the envelope components of buildings (both newly put into service and being in service). Thanks to the miniaturization of the equipment this method is also suitable for: detecting damp areas in a structure and locating their damage as well as to evaluate the quality of the thermal insulation of concrete structures. The tests do not involve contact and the infrared radiation distribution image obtained from the thermal imaging camera is recorded in the form of thermograms which are then subjected to analysis. This method cannot be used under some weather conditions, as described in [42].

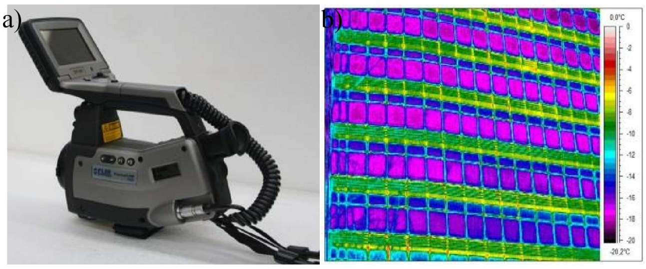

Fig. 13. Thermal imaging camera (a) and typical thermogram (b)

2.9. Proof loads. Tests of concrete structures under static or dynamic proof loads can supply information useful in the assessment of their durability. This particularly applies to important structures (e.g. bridges) subjected to periodically repeated loads or fitted with systems continuously monitoring changes in their condition [4, 43].

3. Taxonomy of SDT methods

Classification criteria. A general classification of the basic semi-destructive methods (SDT) suitable for assessing the durability of concrete structures is proposed in Fig. 14. Physical, chemical and biological methods have been distinguished and divided into the ones suitable for field tests and for laboratory tests of samples taken from structures. Table 3 shows the proposed original taxonomy of semi-destructive methods together with the range of their application for identification of the durability of concrete structures.

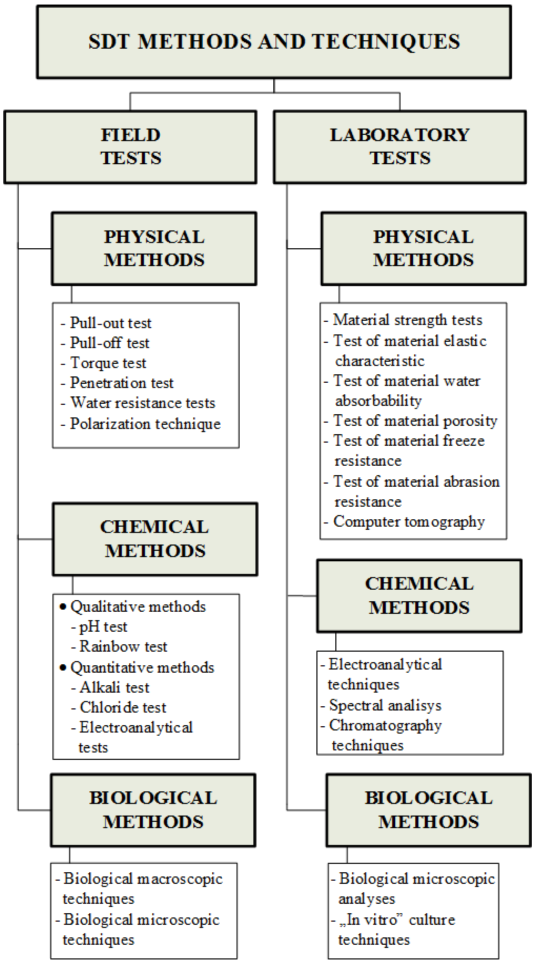

Fig. 14. Basic semi-destructive testing (SDT) methods and techniques useful in assessing durability of concrete structures

3.1. Field tests. Field tests are most often based on physical and chemical methods. The most popular physical methods comprise diagnostic procedures for evaluating the strength parameters of concrete, particularly its compressive strength f_c, on the basis of the force pulling out an anchor (previously embedded or installed in a borehole in the concrete) using the pull-out method and torque tests, and pull-off adhesion f_b by the pull-off method consisting in measuring the force pulling a metal disk off the concrete substrate. The methods have been successfully used for many years and have been described in detail [44] and standardized [45]. The latest set for pull-off testing is shown in Fig. 15 [46].

The physical methods can also be used to determine the resistance of concrete to the penetration of chloride salts as well as its water resistance. Penetration tests and water resistance tests are used for this purpose. Among the penetration methods, the methods described in detail in [47] and standardized in [48, 49] deserve special attention.

Particularly popular is the Windsor probe method used since the 1960s. The method can be used to estimate the physical parameters of concrete on the basis of the depth of penetration of a calibrated ball drilled into the concrete [50]. Another version of this methods is the Pin Penetration Test developed in the 1990s [51].

Semi-destructive electroanalytical tests, mainly suitable for evaluating the degree of corrosion of the reinforcement in reinforced concrete structures, include the linear polarization technique (LPR) consistent with [52, 53]. The LPR method, directly providing a reliable result, consists in measuring the corrosion current. But the test equipment used in this method requires direct contact with reinforcement steel.

Chemical methods are used to determine the chemical constitution of concrete on the basis of material samples taken in situ. The most popular techniques are: the pH test, rainbow tests and chloride tests. Most of the kits for measuring the pH of concrete are based on the visual comparison of the colour on the litmus paper [54]. There are also available modern pH test kits which include a measuring electrode as shown in Fig. 16a.

The degree of carbonization of the reinforcement concrete cover can be simply evaluated by taking a concrete sample and determining its pH by means of a pH-meter.

The measuring electrode in chloride test kit is shown in Fig. 16b. Using this test one can determine on site in a simple way the chlorides content, the depth of their penetration and their distribution in the cross section of a concrete element. The testing procedure is described in [56–58]. This method is usually used in combination with other test methods in order to comprehensively assess the condition of a structure.

Table 3
Phenomena influencing durability of concrete structures, identified by means of SDT methods

	SDT methods	Phenomena influencing durability					
		Structure geometry	Material macro- & microstructure	Mechanical parameters of material	Discontinuity of material	Water & gases resistance	Chemical constitution
Field tests	Pull-out tests	–	–	■	–	–	–
	Pull-off tests	–	–	■	–	–	–
	Torque tests	–	–	■	–	–	–
	Penetration tests	–	–	■	–	–	–
	Water resistance tests	–	□	–	–	■	–
	Polarization technique	–	–	–	–	–	■
	pH tests	–	–	–	–	–	■
	Rainbow tests	–	–	–	–	–	■
	Alkali tests	–	–	–	–	–	■
	Chloride tests	–	–	–	–	–	■
	Electroanalytical tests	–	–	–	–	–	■
	Biological macroscopic techniques	–	□	–	□	–	–
	Biological microscopic techniques	–	□	–	□	–	–
Laboratory tests	Material strength tests	–	–	■	–	–	–
	Tests of material elastic characteristics	–	–	■	–	–	–
	Tests of material water absorbability	–	□	–	–	■	–
	Tests of material porosity	–	■	–	–	■	–
	Tests of material freeze resistance	–	–	■	–	–	–
	Tests of material abrasion resistance	–	□	■	–	–	–
	Electroanalytical techniques	–	–	–	–	–	■
	Spectral analysis	–	–	–	–	–	■
	Chromatography techniques	–	–	–	–	–	■
	Biological microscopic analyses	–	□	–	□	–	–
	"In vitro" culture techniques	–	□	–	–	–	□

■ – basic method, □– additional method, – not applicable

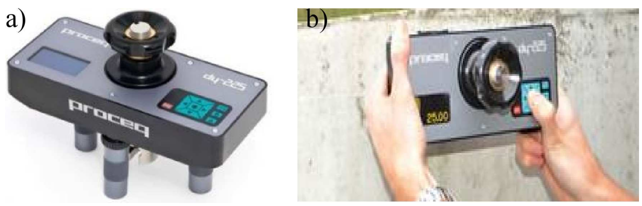

Fig. 15. View of: a) latest set for pull-off testing, b) test being performed (Ref. 46)

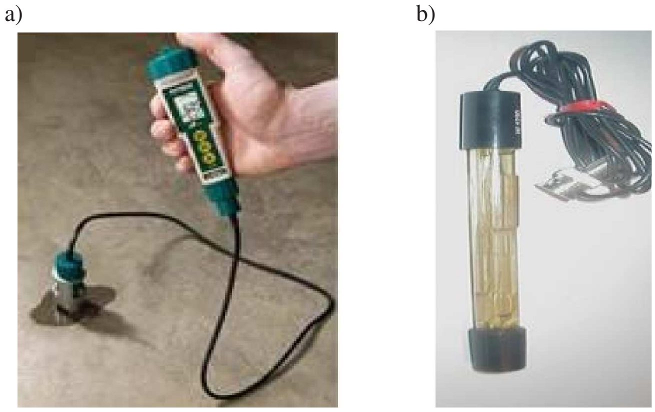

Fig. 16. View of: a) test being carried out by latest kit for estimating pH of concrete (Ref. 55), b) measuring electrode in chloride test kit (Ref. 57)

The rainbow test is used to determine the extent of carbonization of the near-surface layer of concrete. The carbonization depth and the carbonization degree distribution along the depth of the tested element need to be determined when: assessing reinforced concrete structures to establish the causes of their corrosion, estimating the remaining service life when the degree of corrosion is a critical factor and monitoring the effectiveness of the re-alkalization of the concrete cover. Figure 17 shows a drilled core taken from a concrete structure, with a marked concrete carbonization depth determined by the rainbow test.

Fig. 17. Drilled core with carbonized concrete marked using rainbow test (Ref. 56)

Biological methods are used when living organisms, such as microorganisms (bacteria, fungi, etc.) or plants occur on a concrete structure. In field tests macro- and microscopic techniques are used to identify such organisms [59].

3.2. Laboratory tests. The commonly used physical laboratory methods are: material strength tests, assessments of material elastic characteristics, tests of material porosity, material freeze resistance and material abrasion resistance. The latest method in this group is computer microtomography, which makes it possible to reconstruct a three-dimensional image of material microstructure of the tested sample on the basis of two-dimensional projections obtained by scanning it with a beam of X-radiation [60] (Fig. 18).

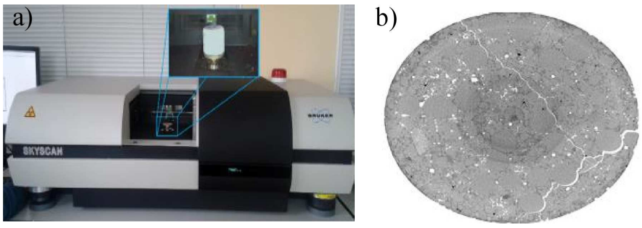

Fig. 18. View of computer X-ray microtomography test setup (a) and obtained image of concrete sample cross section (b)

From among the laboratory chemical methods the rapid chloride permeability test (RCPT) (Fig. 19) deserves attention. Concrete samples placed in a special measuring chamber are subjected to this test in accordance with a standardized procedure [61].

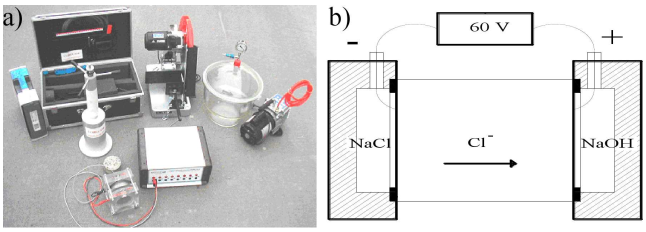

Fig. 19. Rapid chloride permeability test (RCPT): a) test set (Ref. 57), b) principle of operation

Besides being used to identify the type of living organisms, laboratory biological methods, such as: advanced microscopic analyses and "in vitro" culture techniques, are used to determine the way the living organisms affect concrete structures [62, 63]. Autotrophic organisms, which are able to synthesize organic compounds from the simple inorganic compounds constituting concrete components, and heterotrophic organisms, feeding on compounds obtained from enzymatic chemical changes of the structural material, are distinguished.

4. Development of concrete structures durability diagnostics

One of the major trends in the development of non-destructive methods of determining the durability of concrete structures is the automation of diagnostic tests [64]. Successful attempts have been made to construct various scanners and robots (Fig. 20) for this purpose, which considerably speed up the measuring procedures and make them more efficient.

Another important development trend is carrying out tests with the simultaneous use of two or even three methods (multi-modal testing and data fusion), whereby the reliability of the tests results is increased, as reported in many papers [18, 35, 65].

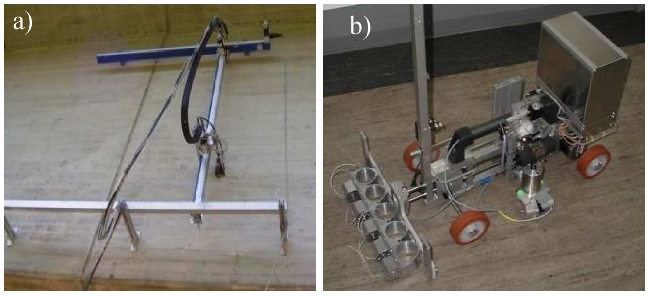

Fig. 20. Examples of: a) scanners for testing vertical concrete surfaces, b) robots useful in non-destructive testing of large flat concrete elements (Ref. 64)

Attempts at automation and data fusion stimulate the development of advanced IT tools for the analysis and interpretation of the test results simultaneously obtained by several non-destructive methods.

Furthermore, today in the case of many measuring methods and sets, wireless systems are routinely used instead of the traditional transmission cables connecting the measuring device with the unit recording and analysing the test results.

5. Conclusions

Thanks to the wide (continually extended) range of methods and techniques for the testing of concrete structures their current condition can be increasingly more precisely diagnosed. The presented correlations between the principal factors having a bearing on the durability of a structure and the basic test methods and techniques illustrate the current diagnostic possibilities.

A much more complex problem is the prediction of the durability of a structure, since it is encumbered with uncertainty as to the future degradation mechanisms which will be acting on the structure and the effects of the mechanisms. In order to improve the predictive procedures further intensive research on the modelling of degradation phenomena on the basis of NDT and SDT results is needed. The use of artificial intelligence (artificial neural networks, genetic and imperialist algorithms) for this purpose is highly promising [66–70].

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