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Assessment of the decay extent for reinforced concrete elements by using non-destructive methods

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Summary

The need to investigate reinforced concrete buildings by using non-destructive methods is a topical issue in the field of construction. This paper presents the most representative non-destructive methods that are applied in the investigation of the reinforced concrete elements / structures, in order to identify the decay extent. The first part of the paper presents and classifies, according to their origin, the main factors leading to the degradation of the concrete elements. In the second part, four investigation methods are described, that are most frequently used for identifying and quantifying the damages of reinforced concrete elements.

Keywords: reinforced concrete, decay extent, non-destructive methods, investigation.

1. INTRODUCTION

The non-destructive methods used for the investigation of the degradation process are a topical problem in the field of civil engineering. The use and development of these methods arise from the need to evaluate the reinforced concrete structures without damaging their components.

The paper presents the principles underlying the development of the most commonly used non-destructive investigation methods, both with their advantages and limitations. These methods can be successfully applied for both existing and under execution buildings. The situations in which the use of these methods is recommended for buildings under execution are [1,2,3]: (i) material quality control (if there is doubt about their performance), (ii) verification of concrete compressive strengths at certain intervals (iii) establishing the possibility of applying external loads (removing the supports, the formwork or pre / post-compression steps), (iv) eliminating uncertainty regarding the location of the reinforcement elements (localization, dimensions and thicknesses of the covering layer).

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Also, non-destructive investigation methods are recommended for buildings in service stage, in the following cases [1,2,3]: (i) verification of concrete quality with regard to internal defects (segregation, gaps, exfoliation), (iii) verification of physical degradation (freeze-thaw, high temperature, shrinkage and cracking), chemical attack (the action of some acids, salts, the reaction), (ii) checking the reinforcements which are embedded in concrete (location and dimensions) (iv) assessment of the mechanical properties of the concrete, (v) identification of the homogeneity of the concrete for core extraction (if a correlation between the non-destructive and the destructive methods is attempted).

2. DEGRADATION FACTORS SPECIFIC TO REINFORCED CONCRETE ELEMENTS

Concrete is a complex construction material and its main performances are the compressive strength and the durability [1]. These characteristics are directly influenced by the composition of the concrete (water-cement ratio, permeability, density etc.) and by the exposure conditions to the environmental agents (in terms of intensity and duration). The durability of concrete elements describes the ability to maintain their designed performances under environmental factors, possible chemical attacks, or under the effect of mechanical wear.

The term "decay" in the construction field is considered as any change in the physical, mechanical and / or chemical characteristics of the materials, elements or the whole assembly that may decrease their strength, stability or durability [2]. The most common degradation factors, specific to reinforced concrete elements are shown in Table 1 [4].

Table 1. The main risk factors for reinforced concrete constructions [4]

Risk factor	**Factor nature**	**Timing**	**Presence probability**
Natural factors			
Depth of rainfall, solar radiation	physical	long-term	continuous cycles
Humidity and temperature	physical	long-term	continuous cycles
Wind, tornado, hurricane	physical	fast onset	rare / infrequent
Soil movement	physical	long-term	continuous cycles
Earthquake	physical	fast onset	rare / infrequent
Landslide, volcanic eruption	physical	fast onset	rare
Factors resulted by human - construction - environment interaction			
Pollution	chemical	long-term	continuous cycles
Improper handling/use	physical	long-term	continuous cycles / frequent
Lack of maintenance works	chemical / physical /	medium / long-	continuous cycles

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	biological	term	/ frequent / infrequent
Design / execution errors	chemical / physical	medium / long-term	continuous cycles / infrequent
Inadequate / lack of intervention works	chemical / physical / biological	fast onset / long term	infrequent
Human hazards (theft, war, terrorism, accidents)	chemical / physical / no limits	fast onset / medium term	rare / infrequent / continuous cycles

3. NON-DESTRUCTIVE TEST METHODS FOR ASSESSING THE DECAY EXTENT OF R.C. ELEMENTS

Nowadays, concrete is one of the most frequently used construction material, due to its superior ratio between performances and costs. This leads to the need of developing non-destructive methods for verifying the quality of the concrete as a material, of single elements and moreover, of the structure as a whole system.

Assessing the damage/decay extent of concrete elements can be achieved by applying a relatively large number of non-destructive test methods (NDT). Nevertheless, each of these methods can give answers only to specific uncertainties regarding the performance of the investigated element. Thus, a very important stage consists in approaching the specific principles, advantages and limitations for each NDT method. Therefore, the modern construction technology requires operators with a good understanding of the principles underlying the non-destructive methods, the use of equipment for optimal identification of the parameters that are being investigated, as well as the interpretation and correlation of the provided results [5].

3.1 Non-destructive methods for concrete investigation

Table 2 presents the most commonly used non-destructive test methods for the investigation of the concrete structures, referring to the specific parameter, their advantages and disadvantages.

Table 2. Non-destructive methods for concrete investigation

Investigation method	Parameter	Advantages	Disadvantages
Visual method	flaw detection at concrete surface	easy, accessible equipment, simple to carry out	experience needed; only surface defects are detected; reduced accuracy
Ultrasonic pulse velocity (UPV)	mechanical strength estimation, identification and	accessible, portable, fast, easy-to-operate equipment	results are influenced by different factors; skills required for both, equipment usage and

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	estimation of defect size (voids, cracks, joints)		result evaluation
Impact-echo method	flaw detection and depth estimation; rebar location	requires access to one side of the element; accurate and fast	skills required for both, equipment usage and result evaluation; limited thickness of elements
Rebound hammer method (RH)	determination of strength and concrete homogeneity	easy to apply, portable and easy-to-operate equipment	low accuracy; concrete age, carbonation, aggregates and humidity are influencing the results
Electromagnetic induction method	position and diameter of bars; concrete cover thickness determination	easy to apply, portable and easy-to-operate equipment	accuracy of estimated cover depth is affected by the spacing between bars; used for the first reinforcement layer
Radar method	determination of layer thickness for different densities, flaw and metal detection	fast scanning using non-contact antennas; requires access to one side of the element	limited region and depth of investigation; skills required for results evaluation; not easy to detect delamination and cracks
Radiography	flaw and concrete homogeneity detection	provides an image with the internal structure of the element	bulky and expensive equipment; highly skilled operators; requires access to both sides of the element
Thermal method (infrared thermography)	flaw detection (voids, cracks, segregation)	covers greater areas; results provide an indicator of the deteriorated area; easy-to-operate equipment	depends on the environmental conditions; limited depth of investigation; skills required for results evaluation
Half - cell potential	determine the corrosion occurrence	portable, lightweight equipment, indicates corrosion activity	no indication of the corrosion rate; requires direct contact to the reinforcement
Linear polarization	indicates the rate of corrosion at the time of testing	simple, portable, lightweight equipment; indicates the rate of corrosion at the time of testing	skilled operator; requires direct contact to the reinforcement; cover depth no more than 100 mm; smooth, uncracked concrete and free of moisture

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In the following sub-chapters, four of the most important non-destructive investigation methods are detailed, depending on their applicability and use in identifying the concrete decay extent.

3.2 Ultrasonic pulse velocity (UPV) method

The principle underlying the method is the property of ultrasonic waves to propagate at different speeds in materials with different densities. The transmitted signal will be influenced by the intersected defects, by changing the velocity and the propagation period. The method is used to identify concrete defects (inhomogeneities, gaps), to quantify the decay extent [6], but also to estimate the mechanical properties of concrete (modulus of elasticity, compressive strength). The norms governing this non-destructive method are given in [7,8,9].

The method involves the use of two transducers, a transmitter and a receiver. They are positioned on the surface of the element (Figure 1), perpendicular to the direction of concrete casting, and a coupling medium (usually petroleum jelly or a product based on mineral oil) is applied to the contact area. For short measuring distances of up to 50 cm, the frequency of the transducers used is between 60 and 200 kHz and in the case of very large distances between the transmitter and the receiver, up to 15 m, their frequency will be between 10 and 40 kHz [8, 9].

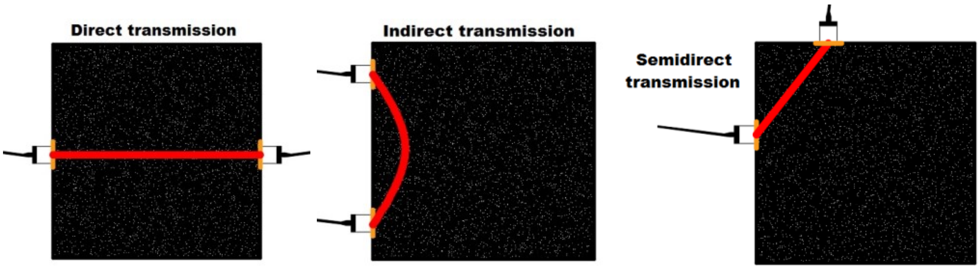

Figure 4. Modes of transmission for the ultrasonic pulse

In 2012, Agunwamba & Adagba [10] correlated the speed of the ultrasonic pulse with the condition of the investigated concrete (approximately 2400 kg / m3), based on Whitehurst's 1951 research [11]. The impulse speed, as a concrete quality indicator, is shown in Table 3.

Table 3. Concrete quality assessment based on ultrasonic pulse velocity

Concrete quality	Ultrasonic pulse velocity (m/s)
Excellent	Over 4500
Good	3500 – 4500
Doubtful	3000 – 3500
Low	2000 – 3000
Very low	Under 2000

The method is influenced by the temperature of the concrete, which can reduce the signal propagation velocity, but variations in speed are neglected for temperatures between 10 ° - 30 ° C. Concrete humidity is also another factor influencing the wave velocity, being about 5% higher for saturated concrete than for dry concrete. Consequently, the results provided may have errors of up to 20% [12].

3.3 Radar method

In the field of constructions, especially in the investigation of reinforced concrete structures, the method is used to locate areas with segregations, defects inside the elements (exfoliations or voids), determination of the thickness of the concrete layer and the position of the reinforcements. The experimental research carried out by Senin and Hamid in 2016 [13] demonstrated the applicability of this method in determining the water and chloride content of reinforced concrete elements, based on the principle of electromagnetic wave amplitude attenuation.

The radar method is based on the propagation of electromagnetic energy in materials with different electrical properties. Propagation of the wave is influenced by two properties of the material: electrical conductivity and dielectric constant. Objects or areas inside the material with distinct electrical properties will reflect electromagnetic waves differently, which will indicate the existence of defects. Low frequency waves penetrate the depth of the elements, while high frequency waves are used for better response resolution to low-density concrete elements [14].

In a radar system, the main quality factor is the antenna, which acts both, as transmitter and receiver. This influences the quality of the received data, the resolution and the depth of penetration of the waves. For the application of the radar system to concrete elements, the frequency of the antenna is between 500 and 1500 MHz [3]. If the antenna is positioned directly on the surface of the element, the depth of investigation increases.

The in-situ applicability of the radar method is limited by atmospheric conditions and by the surface moisture, which will lead to an increase in the electrical conductivity of the investigated material. Radar waves are absorbed by metals, so the results of the investigation are directly dependent on the reinforcements embedded in the concrete element [15]. The method does not provide information about the diameter of the reinforcements, and in some cases, small defects in the interior of the concrete elements can be unidentified [3,15]. Using the equipment and interpreting the results requires a high level of qualification and the costs are relatively high.

3.4 Infrared thermography

The principle of the method consists in collecting the infrared radiation emitted by the surface of the concrete, converting it into electrical signals and creating a thermal temperature distribution image [16]. The method is used to identify defects

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in the structure of concrete elements (cracks [17], segregations, voids, exfoliations in the concrete cover layer), but also to identify the position of the reinforcement in the case of a concrete layer of normal size (maximum thickness of about 3.8 cm) [18]. A void filled with air or water inside the concrete element, releases the heat to the surrounding environment much faster and can be observed in the thermal image through a lower temperature zone.

The infrared thermography device has four main components: (i) the infrared recording camera, (ii) the real-time scanning microprocessor connected to a display screen, (iii) the data acquisition system, and (iv) the data storage system (thermal or visual, for further processing) [3]. The thermal method is influenced by the environment (solar radiation, wind, dust) and by the material characteristics.

For the in-situ application of the method, Aggelis & all. [16] demonstrated that an auxiliary heating source is required if the solar radiation is not sufficient to bring the investigated surface to a high temperature. Also, the investigation procedure is not performed under the direct action of sunlight, rain or wind, influencing the results. In another experimental study, Aggelis & all [17] pointed out that a higher temperature of the investigated element (approximately 70-80 °C) provides more accurate information about the decay extent compared to those obtained at lower temperatures (about 60 °C).

Keo & all [18] successfully applied the thermal method in combination with a heating source (a system consisting of a microwave generator with a power of 800 W at the frequency of 2.45 GHz and a horn-type pyramid antenna) for identifying the reinforcing bars having diameter of 12 mm, spaced at 100 mm. At the moment, the experiment [18] cannot replace the utility of the pachometer (rebar locator), the application of which is more simple and efficient. The thermal method does not affect the concrete and can generate development perspectives for the in-situ application, in order to inspect other parameters of reinforced concrete elements than the decay extent (positioning and diameter of the reinforcement, determination of the thickness of the concrete cover layer etc.).

3.4 Impact-echo method

The principle of the method is based on the measurement of the shock wave generated by the impact of a hammer, having standard sizes, on the surface of the investigated concrete. The frequency and amplitude of the waves generated by the impact change depending on the strength and homogeneity of the concrete, the presence of defects or reinforcement.

The impact of the hammer generates the shock wave whose amplitude and frequency is recorded by a transducer located in the vicinity of the impact area. The shock wave is reflected if a defect or a reinforcement bar is intersected, and the amplitude of the spectrum will show a peak in that area. Fast Fourier Transform (FFT) is used to obtain amplitude spectrum [12]. Knowing the wave propagation velocity in a homogeneous and "healthy" material such as concrete (v_p) and peak

amplitude (f_p), we can calculate the depth at which the discontinuity is inside the element. The results obtained are influenced by the type and duration of the impact. Thus, the shorter the impact time (t_d), the higher the frequency of the shock wave.
The method requires access to one side of the element (plate or road pavement), it is fast and accurate. It is used to identify and locate defects in reinforced concrete elements, hollows in multilayer elements, to determine the thickness of concrete layers [6] or to check voids in pre-tensioned reinforcement pipes, injected with cement paste, from the bridge structure.
In 2010, Matsuyama & all [19] applied the echo impact method to identify voids in reinforced concrete pillars in the structure of a highway. The results are not influenced by the presence of reinforcements, and after the test were identified areas with exfoliations between pre-stressed reinforced concrete panels and reinforced concrete pillars.
The accuracy of the results decreases with the increase of the investigation depth, and errors in estimating the decay extent will have a higher value for investigations into the depth of the element.

4. CONCLUSIONS

This paper presents the most representative non-destructive methods for the investigation of the reinforced concrete elements / structures. Table 2 presents a summary of the main non-destructive investigation methods along with the specific advantages and limitations.

Knowing the specific principles of applying non-destructive methods is an advantage for establishing an investigation plan and for increasing the efficiency of the testing process with respect to time, costs and expected accuracy of the result.

By the comparative analysis of the non-destructive methods for the investigation of the reinforced concrete elements, the following conclusions are highlighted:

1. The ultrasonic pulse velocity method is applicable to a wide spectrum of reinforced concrete elements, characterized by an easy-to-use methodology; The results that are obtained have a high degree of accuracy providing essential information regarding the decay extent; Instead, the method is limited by the degree of roughness of the support layer, the need of a coupling medium and the moisture and temperature of the investigated element surface;

2. The in-situ application of the thermal method is conditioned by the existence of stable environmental conditions and of an external source of heat, in order to easily reveal the existence of possible defects in the structure of the investigated element;

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3. The radar method requires access to a single face of the element, but involves high costs and the results are difficult to process, being characterized by a large amount of data;

4. The impact-echo method is used to identify and locate a wide range of defects, but it requires very skilled operators for result interpretation and the depth of investigation is relatively limited.

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