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Non-destructive evaluation (NDE) methods used for condition assessment of concrete structures

Shouheng Ji

School of Civil Engineering, Tianjin Chengjian University, Tianjin, 300384, China

20593295@qq.com

Abstract. As an integral part of the construction industry, concrete is an important part of the building materials industry, as well as an important material for infrastructure and engineering construction projects. It is widely used in various industries. In recent years, with the improvement of the quality awareness of the whole people, the engineering quality inspection has also received more attention. The previous concrete quality inspection methods have different degrees of damage to the original structure. This paper focuses on the state of concrete structure and its detection method, and introduces the EDN technology. At the same time, through comparison, practical experiment, theoretical research and other research methods to describe EDN technology. Based on the research results, it is concluded that ECN technology can provide a more comprehensive concrete quality report, which is beneficial to the maintenance, repair and restoration of Bridges and old buildings, and help engineers use.

Keywords: concrete, EDN technology, bridge repair, rebound test, ultrasonic testing, acoustic emission, engineering testing.

1. Introduction

Today, there are thousands of publicly controlled concrete structures in China, many of which have existed for several decades. Equally, the number of concrete structures, including bridges and buildings, is increasing each year significantly due to rapid real estate development and urbanization. The movement from rural to urban areas has resulted in a sharp increase in urban residents. Urbanization and the need for bigger residential space have increased the need to construct new structures, such as bridges and buildings [1]. Likewise, concrete structures have been replacing structures made up of clay bricks, wood, and other primitive materials all over China. Testing the quality of concrete at different stages of the life cycles of a structure is crucial in ensuring the safety of the people using such structures. Thus, to properly rehabilitate, maintain, and repair public infrastructures, engineers must use effective structure assessment methods [2]. Better inspection methods are required for deteriorating as well as newly constructed infrastructures. There are several new and emerging techniques for evaluating the quality of concrete in the civil infrastructure. Some of these methods include ultrasonic wave, acoustic emission, microwave, and rebound methods, among other techniques. All of these methods are non-destructive, meaning that a building or any other structure being tested for the quality of its concrete remains intact, and its integrity is maintained [2]. The traditional methods have several limitations, making it difficult for engineers to predict results immediately after the test. Specimen concrete, in some instances, differs from the actual structure and the strength properties of specimen concrete are usually

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affected by shape and size, which can result in inaccurate conclusions [2]. Thus, various non-destructive evaluation (NDE) techniques have been devised to overcome these limitations. NDE techniques are premised on the fact that it is possible to relate some chemical and physical properties of concrete to the durability and strength of structures. Such techniques have existed for the last three decades, and engineers in different countries have used them to evaluate the infrastructure condition [2]. Today, NDE methods have become more advanced as non-destructive testing technology has transitioned from a hammer to impact impulse response and echo to the application of waves such as microwave, ultrasonic, and acoustic emission. The current paper evaluates different NDE methods, such as ultrasonic, acoustic emission, and microwave techniques, among other methods.

2. NDE overview

NDE is a technology that uses techniques to evaluate materials, objects, and systems without impairing their usefulness. Engineers measure or inspect structures without little or no damage to them [2]. Thus, these methods are today considered powerful tools for assessing existing concrete structures' durability and strength. They are drawing increased attention in terms of effectiveness and reliability. Their usefulness in testing in situ is becoming one of their distinguishing features and compared to the traditional technique of random sampling of concrete for analysis of the material, and most engineers prefer NDE. There are different NDE techniques: rebound hammer tests, ultrasonic tests, acoustic emission tests, leak testing, liquid penetrant and magnetic particle [2]. Five significant factors, including required penetration depth, required lateral and vertical resolution, the difference in physical properties between the structure and its surroundings, and past information about the techniques used in constructing the structure under test, influence the choice of the NDE technique.

NDE techniques have various functions, including ranking concrete structures based on their present condition, detecting the state of RC structures and comparing various properties according to threshold values. Civil engineers must have deep knowledge and training on various NDE techniques available for testing the integrity and quality of concrete in different structures. With such knowledge, they will be able to select the best technique from the available methods, depending on the condition of the structure under test [2]. It is important to note that using different NDE techniques to evaluate a given parameter increases confidence and validates the result. Coalescing results of different NDE techniques while evaluating the quality of infrastructure is desirable for better results.

3. NDE techniques

3.1. Rebound tests: rebound hammer test

The rebound test is an NDE category that entails testing the compressive strength of concrete in a given structure. Engineers under this category use the rebound hammer test, also known as the Schmidt hammer [3]. The hammer comprises a spring-controlled metal that moves on a plunger inside the tubular house. Pressing the plunger against the concrete surface result in the spring-controlled metal containing constant energy hitting the concrete surface and rebounding back. The degree of the rebound, which is the measure of the hardness of the concrete surface, is recorded on the calibrated scale. The measured value is typically designated a rebound index or rebound number. The rebound hammer test technique is premised on the hardness and strength of a concrete surface against which a mass strikes influences the rebound of elastic masses [4]. A concrete surface with low stiffness and strength absorbs more energy and yields a lower rebound value. Therefore, one can relate the hardness or stiffness of a concrete surface to the rebound reading and obtain the compressive strength of the concrete under test [4]. Usually, the body of the rebound hammer has a graph from which an individual can directly read the compressive strength of concrete under test.

3.2. Rebound hammer test procedure

The first step during the rebound hammer test is calibrating the hammer, which is tested against an anvil, a steel device with a Brinell hardness value of 5000 N/mm^2. Following the calibration, which is usually done to test the hammer's accuracy, the hammer is positioned at a right angle on the concrete surface of the structure under study and readings are recorded [4]. The hummer is held horizontally at a right angle for vertical concrete surfaces, and readings are recorded. It is crucial to note that holding the hammer at an intermediate angle can result in different rebound numbers for the same concrete surface. The most accurate way of obtaining the relationship between the rebound number and compressive strength of the concrete surface is by testing the concrete cubes utilizing the compression testing machine and rebound hammer simultaneously. The procedure entails first recording the rebound number of the concrete cube followed by testing for compressive test on the compression machine. When the energy's impact of the rebound hammer is approximately 2.2 Nm, the fixed load needed is of the order of 7 N/mm^2 [4]. This indicates that the load should be increased when calibrating the hammer of high energy impact, and when calibrating a hammer of low energy impact, the load should be decreased. Similarly, it is also important to note that the test specimen should be larger enough to reduce the side effects on the test results of the actual structure. Cube specimens of approximately 150 mm are recommended to calibrate rebound hammers of lesser energy impact. For hammers of more significant energy impact, cube specimens of approximately 300mm are recommended. It is advisable to store the cube specimens at room temperature for 24 hours after removing them from the curing pond before subjecting them to the rebound hammer [3]. Following establishing the correlation between rebound number and compressive strength, the strength of concrete can be evaluated. Generally, the rebound number is directly proportional to the strength of the structure. Still, it is essential to note that the rebound number can be impacted by various parameters such as aggregate type, cement type, moisture content and surface condition of the concrete, age and curing of the concrete and carbonation of concrete surface, among other factors. However, the rebound number reflects the compressive strength of a given surface up to a limited depth [3]. Likewise, the rebound number does not indicate the concrete's internal flaws, cracks, or heterogeneity. Thus, estimating concrete strength using the rebound hammer technique does not produce a highly accurate result, and the prediction may be about ± 25 % inaccurate. Obtaining a correlation between compressive strength and rebound number by testing core samples acquired from the structure under test or the standard specimen made from the same concrete materials and mix proportion increases the accuracy of the results.

3.3. Ultrasonic testing

Ultrasonic testing is another NDE technique that engineers can use to perform various tests on concrete to determine its integrity and strength. The test utilizes high-frequency sounds that human ears cannot process. The ultrasonic sounds fall between 16 kHz and 20 kHz depending on an individual's hearing state and health [5]. The ultrasonic technique of testing the quality of concern is based on the principle that sound can travel through solid objects, and depending on the intactness of a material, the quality of sound may differ among different materials. Thus, the sound waves travel through the concrete under investigation using this technique. They detect alterations or flaws in the structure, allowing engineers to characterize the concrete and make crucial decisions regarding repair and maintenance [6]. Most equipment used during ultrasonic testing comprises a standard display device, a transducer, and a pulse system. These elements can be altered, or other devices can be added depending surface examined and the user. The pulse generator produces short impulses directed into the transducer on the equipment, which generates high-speed waves (high frequency), generating ultrasonic energy. The produced energy on the equipment searches for cracks, breaks and other flaws within the concrete. When the interacting waves encounter a discontinuity in the concrete, they change direction slightly (are reflected). The transducer transforms the reflected waves into an electrical signal which is recorded on the graph and can be read directly [6]. Ultrasonic waves occur in various amplitudes and patterns depending on the equipment used and the test performed. Longitudinal designated as P-Waves (pressure waves) waves usually occur in equipment that performs tests in deeper or longer material using high frequencies and short waves. These waves bounce around the material and create excited zones and wavelengths. Such zones are regarded as compression zones and are produced when a wave moves through a body. P-waves typically oscillate in the propagation direction. Transverse waves, also known as S-Waves (shear waves), occur within the material being investigated [7]. They oscillate perpendicularly to the body, meaning that they are propagated at right angles. Other crucial waves include Rayleigh waves (R-waves) and plate waves (Lamb waves), suited for assessing small breaks or defects inside a concrete because they oscillate parallel to the surface. Due to high attenuation in concretes, high-frequency waves ranging between 20-150 kHz are preferable [8].

Using P-waves and S-waves, an ultrasonic system can measure the travel time of waves through a concrete structure [7]. As opposed to uniaxial compression tests, ultrasonic tests do not require the collection of samples from the existing structure. Instead, the test was applied directly to the surface of the structure under investigation without any interference with the structure. Because almost all concrete structure comprises steel rebar, sample with or without steel are evaluated. While steel rebar plays a crucial role in increasing strength and stiffness in concretes, it can be harmful to the structure in the long run [6]. To measure the strength of concrete and possible damage due to steel rebar, the pulse velocity in the ultrasonic system is used to investigate the physical properties of the concrete. The system uses S-waves and P-waves, and since the distance of the concrete under test is already known, it is possible to observe the travel time of ultrasonic pulses using this method [7]. Oil or grease is usually used to eliminate air gaps between the sample material and the transducer for the longitudinal displacement. For shear displacement, oil is not applied because S-waves do not move evenly and effectively through liquids. Some of the features sought in this test include probe frequency, data length, sample rate, pulse data length and pulse amplitude. Other crucial information, such as voids and cracks in the concrete undetectable to human eyes, is evaluated as well [6]. The pulse velocity technique provides the elastic properties of concrete once the velocities of the shear and longitudinal directions are obtained. The ultrasonic technique can also be used to test for reactive powder in the concrete. Concrete composition varies slightly, but concrete always contains vital elements such as cement paste, water, sand, aggregate and other components. Aggregates in concrete usually vary in size ranging from fine to coarse aggregates such as sand and gravel. The usual frequency for typical concrete materials ranges between 20 and 150 kHz [8]. Introducing a new material, for example, reactive powder concrete, the frequency can go as high as 1 MHz because the reactive powder contains fine particles as opposed to coarser aggregate in traditional concrete [9]. Fine particles in the reactive powder change the attenuation in the concrete and permit these higher frequencies. Thus, while testing for the quality of concrete in a structure, it is advisable to test for reactive powder because the concretes with this element are usually of high quality. The reactive powder consists of tiny steel fibers that contribute significantly to the overall strength of concrete [9]. The presence of these steel fibers eliminates the need to use steel rebar.

4. Microwave technique

Microwave is another crucial NDE technique that engineers use to test the quality of concrete, particularly those reinforced by steel rebar —using rebar in the reinforcement of concrete results in corrosion which contributes to delamination and cracking in the concrete. Thus, engineers need to keep examining concrete to ensure it is free from any defect that can lead to collapsing structures such as bridges and buildings, especially those created using traditional technologies such as the use of rebar. Microwave is a trending imaging technique and cheaper than tools such as Ultrasound, Gamma-ray and X-ray. Compared to these imaging techniques, it has low ionizing power and is of lesser frequency, making it cheaper. Microwave comprises a vector network analyzer (VNA), a display unit (computer) and an antenna. The technique is used to reconstruct complex permittivity images in the test objects such as concrete [10]. It utilizes the reflection data obtained by the scattering field within the antenna beyond the object under investigation. During testing, the concrete is radiated with a low microwave field to measure the concrete dielectric properties. The microwave time-domain algorithm plots the dielectric characteristics of the concrete being inspected. This measurement method needs additional information about incident reflection coefficients, usually obtained in advance by placing the metallic plate at varying distances from the antenna. The measurements are carried out to scan the concrete and procedure triggering an antenna using VNA [10]. The S-parameters (scattering parameter) produced on VNA are transferred to the display unit, where imaging and evaluation are conducted. S-parameters and scattering matrix, also known as S-matrix, reflect the electrical behavior of the linear electricity network, while electrical signals offer different steady-state stimuli. The higher the values of S-parameters and s-matric, the lower the concrete's quality, meaning there are cracks and other defects. Thus, the microwave technique, like other NDE techniques, tests the quality of concrete without interfering with its functionality, making it another cheaper option for engineers.

4.1. Acoustic emission testing

Acoustic emission refers to a physical phenomenon where various objects generate elastic waves when subject to the deformation of stress [11]. Thus, the acoustic emission test is based on the principle that it is possible to register the elastic waves and evaluate them to detect deformities or abnormalities within the concrete, such as cracks, breaks and holes. It is a test used by engineers to monitor the quality of concrete in a particular structure to evaluate its repairing or retrofitting possibilities. The method has been used in the structural integrity test on bridges and buildings. An acoustic emission test of concrete's yield point by reflecting fractures, breaks and cracks. The yield point generates stress waves that move through the concrete, with the waves reaching the surface of the concrete being used to simulate the piezoelectric sensor, which in turn converts them to an electrical signal for further assessment. Acoustic emission testing applies sensors that are highly sensitive to internal faults, and because these damages possess parameters that correlate with internal load, engineers can utilize the information obtained from the sensors to evaluate the quality of the concrete [12]. For instance, an acoustic emission test on concretes can help an engineer relate the crack propagation of concrete to its mechanical behavior. The location of micro-cracks and propagation of cracks in concrete can be detected using an acoustic emission test by developing highly localized stresses at the crack tip, which creates stress waves that can be monitored through piezoelectric sensors. Piezoelectric sensors convert stress waves to electrical waves that can be easily evaluated. The extent of damage and cracking in new or old concrete can be evaluated based on the acoustic emission parameters obtained [12]. Some acoustic parameters include acoustic emission event, acoustic emission count, acoustic parameter energy, acoustic parameter arrival time and acoustic parameter source location. There are various acoustic emission test methods. Transient acoustic emission test uses sensors to capture the acoustic emission exceeding the threshold. During this test, things such as emitted wave duration, peak amplitude and signal energy are determined [11]. The technique can be used to detect damages like cracks. Continuous acoustic emission test uses sensors to capture stress waves within a fixed period, for instance, one-tenth of a second. The data obtained is used to calculate the root-mean-squared value and average signal level. The technique is best suited in instances where emission amplitude is low.

Setting up the testing equipment entails placing piezoelectric sensors on the surface of the concrete. Multiple sensors are used due to the fact that different sensors may pick up different wave signals for the same emission event, particularly in complex structures such as concrete [12]. While setting up acoustic sensors, it is usually advisable that each surface of interest is within the range of a minimum of three sensors. Typically, a pattern of interlocking rectangles or interlocking triangles should be used to set up acoustic sensors [12]. Using a fluid couplant is crucial in helping the sensor to obtain stronger signals because it increases the surface area that transmits the force. Some of the liquid couplants used include greases, resins and sealants. Nevertheless, it is essential to note that different liquids work best in different applications. Acoustic sensors are usually connected to the main amplifier, a low-noise preamplifier, and electronic equipment to isolate and filter the sound. This setup is crucial in making the reading more transparent and easier to evaluate accurately. After setting up the equipment, pressure is applied to the concrete, and the system records any acoustic emission above the pre-determined threshold and the time it has occurred. The setup records data associated with signal strength, emission count, emission strength, peak amplitude and other crucial parameters [12]. The distance between the sensor and the source of the wave affects the registered emission strength, and the strength registered by multiple acoustic sensors is usually averaged to obtain an estimate of the strengths of all emissions. From this data, engineers can determine whether or not concrete has cracks, fractures and breaks.

5. Conclusion

To conclude, various NDE techniques have been devised for inspecting and assessing concrete structures to make crucial decisions on the maintenance, rehabilitation and repair of old and new structures, such as bridges and buildings. Engineers use these techniques to estimate the strength and other physical properties, including corrosion and cracks, among other vulnerabilities. Unlike the traditional methods of evaluating the concrete, NDE techniques allow engineers to obtain immediate results of the actual strength and other physical properties of the concrete structures, which help them to make fast and informed decisions concerning the rehabilitation of various structures. For the standard method, specimens cast are tested simultaneously for flexural, tensile and compressive strengths, which makes it challenging to obtain results immediately. Thus, NDE techniques are preferable. The above analysis also reveals that different NDE techniques measure different physical properties of concrete, meaning that engineers should use them concurrently to obtain a more comprehensive report regarding the quality of concrete. For instance, the rebound hammer technique generally assesses the strength of the concrete, and acoustic emission, microwave technique and ultrasonic testing can be used to detect cracks, breaks, corrosion and other damages. Thus, two are these techniques can produce more reliable results.

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